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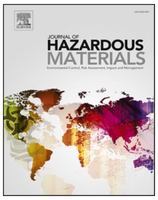

Review

A critical synthesis of current peer-reviewed literature on the environmental and human health impacts of COVID-19 PPE litter: New findings and next steps

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ABSTRACT

Since the emergence of Coronavirus disease (COVID-19), the threat of plastic waste pollution has grown exponentially, with a strong attention on the environmental and human health consequences of millions of personal protective equipment (PPE) (e.g., face masks, shields, gloves, and wipes) being used and discarded. In response, a massive research effort has been launched to understand, characterize, and estimate the exposure risks of PPE associated contaminants. While the number of studies examining the impacts of PPE is increasing, this review aimed to provide a quick update on the research conducted to date of this topic, as well as to identify priorities for future research. Specifically, we analyzed recent global peer-reviewed articles on PPE to synthesize methods, control measures, and documented evidence to (1) investigate the discarded PPE in a variety of environments; (2) determine the microplastics discharge in the aquatic environment; (3) examine the intentionally or unintentionally added chemicals in the production of PPE; and (4) assess potential human health hazards and exposure pathways. Despite progress, more research is needed in the future to fully understand the chemical emissions from PPE degradation mechanisms (mechanical, chemical, and biological), as well as the magnitude and density of PPE pollution in the environment.

1. Introduction

Worryingly, at the time of writing, the global COVID-19 case count had surpassed 191 million, with nearly 4 million casualties and numerous hospitalizations. Many countries continue to rely on billions of personal protective equipment more than a year after the World Health Organization declared COVID-19 a global pandemic. Personal protective equipment (PPE) such as face masks, gloves, and face shields, as well as wet wipes, have been shown to prevent contracting COVID-19 (WHO, 2020). The majority of PPE contains plastics or plastic derivatives, with higher percentages of polypropylene (PP) and polyethylene (PE), as well as other polymeric materials such as polyester, polyurethane, nylon, and polystyrene (Fadare and Okoffo, 2020; Aragaw, 2020). Face masks are used as primary PPE to prevent the spread of COVID-19 disease, and they are classified into several types, including blue surgical masks, dust masks, high grade medical masks (i.e., N95 and KN95), and reusable masks. Face masks made of non-woven or melt-blown fabric can be multilayered (Fadare and Okoffo, 2020; Aragaw, 2020). To keep up with global demand, mass production of PPE has increased worldwide. Disposable face mask production in China, for example, has reached approximately 200 million per day in a global effort to combat the spread of COVID-19 (Aragaw, 2020). Apart from the impact on our physical health, the COVID-19 pandemic has a significant environmental impact via PPE pollution, which we are already experiencing and will worsen as a result of widespread production and use, as well as improper and unregulated disposal of various types of PPE (Adyel, 2020; Prata et al., 2020).

Since the first sightings of PPE on numerous coastal shorelines, the need for research to assess comprehensive data on their abundance and thorough estimation of the associated environmental risks has become clear. This has resulted in the establishment of an entirely new interdisciplinary platform for PPE research, which has grown tremendously

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over the last two years. On the one hand, several rough estimates have quantified waste from used single-use plastic and PPE, as well as calculated the number of face masks to be used and average daily usages in each country (Chowdhury et al., 2021; Haque et al., 2021), which could total nearly 129 billion masks consumed monthly (Prata et al., 2020). Environmental PPE surveys, on the other hand, have already reported the presence of a variety of discarded COVID-19 pandemic items in aquatic and terrestrial environments (Thiel et al., 2021; De-la-Torre et al., 2021; Ardusso et al., 2021; Okuku et al., 2021). Subsequently, a substantial body of research has shown that improperly discarded face masks are a significant source of secondary microplastics upon degradation, particularly micro- and nano-fibers (Shruti et al., 2020; Saliu et al., 2021; Shen et al., 2021; Wang et al., 2021), and that this fraction of (micro-)plastic will continue to rise in the coming years, potentially exacerbating the existing plastic pollution. Because most polymers are not biodegradable, they can remain in the environment for years, acting as a vector for a variety of contaminants and being toxic to organisms. Meanwhile, evidence of intentionally or unintentionally added chemicals in the production of polymer-based face masks is only now emerging (Fernández-Arribas et al., 2021; Sullivan et al., 2021; Liu and Mabury, 2021), indicating that they could be a source of chemicals to the environment. The discovery of these new findings improved our understanding and insight into the fate of PPE under environmental conditions. Despite its potentially important role in shaping public health, PPE, particularly face masks, has emerged as a major environmental and health concern in terms of plastic pollution, including micro- and nano-plastics.

In the midst of COVID-19, we can remark that the scientific community has been working tirelessly on designing strategies and building increasingly active research efforts in multiple directions to bring novel insights into the effects of PPE. The availability of analytical methods has aided researchers in conducting newer research studies on previously unknown harmful aspects of environmental issues associated with PPE items. The breadth of the area of PPE research, as well as the seemingly exponential increase in the number of publications on the subject, can be intimidating to scientists who are new to the field. Furthermore, accurate data requires proper sample processing, identification, quantification, and characterization, and existing methodology differs significantly between studies. It is critical to be well-versed in the currently established new approaches, the application of methods and control measures, and the impact of PPE on the environment and human health in order to identify important, unanswered research questions. In contrast to the reviews that are currently available in the literature, there are no systematic reviews of comparable scope for PPE researchers. Herein, this has prompted us to conduct a systematic scientific-based review of recent advances in PPE environmental research, organized by related topics, in order to establish an integrative perspective of recent advances and provide guidance for future research in this space. Specifically, we analyzed recent global peer-reviewed articles on PPE to synthesize a comprehensive overview of available methods, control measures, and documented evidence on (1) investigation of the discarded PPE in a variety of environments (Section 3); (2) determination of the microplastics discharge in the aquatic environment (Section 4); and (3) examination of the intentionally or unintentionally added chemicals in the production of PPE (Section 5). In each section, we also highlight future directions. Finally, we evaluate potential human health hazards and exposure pathways using evidence from the current literature. We anticipate that this review will assist those interested in PPE research in identifying methods and contributions that will be useful in the development of their own investigations. Furthermore, we hope that this review will attract researchers from various disciplines to gain a comprehensive understanding of recent advancements and challenges in the field, as well as inspire new ideas and research directions.

2. Database search, inclusion and exclusion criteria, and results

We developed a set of keywords to enable a comprehensive search of all peer-reviewed articles on PPE pollution and its associated contaminants. These keywords included COVID-19 pandemic, PPE, face masks, wipes, gloves, chemicals, microplastics, degradation, nanoplastics, metals, additives, plasticizers, and organic compounds. We searched peer-reviewed published papers in scientific databases such as Web of Science, Google Scholar, and Pubmed in July 2021 using Boolean operators and the keywords indicated above. The articles published between December 2019 and July 2021 were first narrowed down from the search results. After reviewing the title, abstract, and content of the papers, review articles, discussion, editorials, focus, commentary, viewpoints and papers that have not been published in English were omitted. In addition, estimates of PPE waste for individual parts of the world that lack environmental monitoring fall outside the scope of this review and were excluded. Furthermore, preprint articles that were available on the internet were eliminated. The remaining publications were then carefully evaluated, and studies that did not undertake experiments on PPE in relation to micro- and nano-plastics and chemicals were excluded. By this way, we were able to select a total of 22 peer-reviewed journal articles that described the prevalence and abundance of PPE in environment ($n = 9$), the attribution of PPE to micro- and nano- plastics ($n = 9$), and the presence of organic and inorganic contaminants in PPE ($n = 4$). Table S1 provides a compiled list of publications organized by the type of PPE research. All data, including current analytical methods, sampling procedures, sample processing, quality assurance and quality control (QA/QC) measures, and documented results were extracted from these articles and organized in Tables 1–3 and Fig. 1.

3. PPE survey and abundance in the environment

3.1. Methodology

Since the detection of COVID-19-related PPE wastes on the world's shorelines, there has been an increased interest in determining and comprehending the extent to which these wastes accumulate in the environment. Depending on the resources available and accessibility to a region of interest, a PPE litter monitoring survey can be either nationwide or regional with the goal of collecting daily/weekly data from both aquatic and terrestrial environments. There is currently no internationally accepted standard procedure for surveying PPE debris. As a result, the sampling methods of the PPE survey have varied depending on the habitat (marine or urban) and the specific objective of the study (floating PPE debris) (Table 1). Six of the nine studies examined the amount of PPE along the shorelines by monitoring marine beaches, whereas other studies focused on floating PPE debris in water (river or marine) and improperly discarded PPE in streets of metropolitan cities near schools, hospitals, and residential areas (Fig. 1a) (Ryan et al., 2020; Ammendolia et al., 2021). While transects and quadrats were commonly used for PPE monitoring along coastal shorelines (Haddad et al., 2021; De-la-Torre et al., 2021), tools such as manta trawls and deep nets were used to investigate floating PPE debris (Okuku et al., 2021; Cordova et al., 2021). It is strongly recommended to conduct the beach survey early in the morning before personnel clean them, and it also applies to surveying PPE litter in streets of metropolitan cities and urban areas. The PPE survey was mostly conducted along the entire beach, with some variations in the areas covered for item collection. Thiel et al. (2021) collected PPE washed up by the last high tide along the last strand line, while other researchers traversed the entire width of the beaches from the edge of the water up to 2 m into the vegetation (Rakib et al., 2021; De-la-Torre et al., 2021; Okuku et al., 2021). In the case of a street survey, PPE litter was collected as close to the street margins as possible. In addition to manual collection by researchers, a citizen science program involving volunteers for PPE litter

Table 1
Personal protective equipment in the environment: methods and evidence from recent global reports.

Study location	Environment	Sampling location	Duration	Methodology	Key findings	Reference
South Africa	Urban	Street	50 days (April – June 2020)	Litter was collected from 400 m of street margins	1. Face masks and gloves contributed $<$ 1% of total mass 2. Found wet wipes amid other PPE	Ryan et al. (2020)
Persian Gulf	Coastline	Coastline	40 days (November – December 2020)	Used transects for each sampling site	1. Blue face medical masks (57 – 63%) in different sampling times (n = 4) 2. 10% of them were torn and damaged.	Akhbarizadeh et al. (2021)
NE Chile	Beach (tourist)	Shoreline	109 days (April – July 2020) 90 days (December 2020 – March 2021)	1. Strandline along the entire length of the beach (1.68 km) was surveyed for face masks 2. Face masks in a stretch of approximately 5 m along the strandline were counted and removed	1. Face mask density of 0.006 ± 0.002 m^{-2}; winter (0.2 face masks km^{-1} d^{-1}) $<$ summer (3 face masks km^{-1} d^{-1}) 2. 89.8% of masks were single use.	Thiel et al. (2021)
Jakarta Bay, Indonesia	Riverine outlets	River water	Every 10 days; March 19, March 28, April 7, and April 15, 2020	1. A 75 m-long, 1.5 m-deep net with a 5 cm mesh size were placed across each river during low tides for 15 min	1. PPE constituted 16% of total debris 2. Face masks of type cotton, sponge, and medical constituted 9.3% of total debris (492 ± 99 items d^{-1}) 3. Other PPE items found including medical wrap, gloves, hazard suit material, and face shield	Cordova et al. (2021)
Bangladesh	Beach	Coastline	84 days (November 2020 – January 2021)	Used transects upto 2 m vegetation for each sampling site Sampled area: 516,683 m^2 of sampled area	1. Face masks: 97.92% of total PPE collected, 2. Density: 6.29×10^{-3} PPE m^{-2}	Rakib et al. (2021)
Peru	Beach	Coastline	84 days	Used transects upto 2 m vegetation for each sampling site Sampled area: 110,757 m^2 of sampled area	1. Density: 0–7.44×10^{-4} PPE m^{-2} face masks were found in 11 beaches 2. -A total of 26 wet wipes were counted in urban beaches, Lima 3. Face shields contributed 6.5% of total PPE	De-la-Torre et al. (2021)
Canada	City	Street, under cars, residential areas, grocery, and hospital zones	May 27 – June 30 2020	Collected debris that was $\sim$1 m and $\sim$5 m from the closest edge of the sidewalk	1. Face masks constituted 31% (n = 274) of total plastic debris 2. 95% of disposable face masks, 3% reusable masks, and only 2 high-grade masks such as N95 and KN95 3. Disinfecting wipes constituted 25% of total plastic debris	Ammendolia et al. (2021)
Kenya	Beach	Coastline Floating litter survey	June 2020	1. Surveys traversed the entire width of the beaches from the edge of water up to 2 m into the vegetation 2. Floating litter trawl surveys were carried out using a 300 μm mesh sized Manta trawl net fitted with a flow meter.	1. Wet wipes and single use masks were the most common plastic litter items found on the beaches of Mkomani and Nyali	Okuku et al. (2021)
Morocco	Beach	Coastline	112 days (01 February – 30 May 2021)	Methodology as described by De-la-Torre et al. (2021)	1. Face masks: 98.4%; Reusable cloth masks: 1.6%. 2. Density: 1.13×10^{-5} PPE m^{-2}	Haddad et al. (2021)

PPE: Personal protective equipment.

sampling on beaches or city streets is regarded as a valuable approach for a national and local survey. Two of eight studies for daily PPE surveys used such citizen science programs (Ammendolia et al., 2021; Thiel et al., 2021). It should be noted that the time frame observed here for the global PPE survey may represent a majority of the period between April 2020 and May 2021. Nonetheless, the sampling period varied between studies, ranging from 4.7 (approximately 33 days) to 16 weeks (112 days). After data collection, the PPE density was calculated by using the formula: $C = n/a$, where C is PPE density (PPE m^{-2}), n is the number of PPE, and a is the covered area (m^2).

3.2. Safety health risk measures

There are significant health risks associated with the COVID-19 survey of discarded PPE in the environment, such as the possibility of SARS CoV-2 transmission via handling or contact with PPE litter, and strict safety procedures must be implemented. Only two of the eight studies mentioned the safety measures adopted during sampling (Thiel et al., 2021; Ammendolia et al., 2021). The researchers followed the social distancing by working in small groups or when there were few people outside. The PPE litter should be handled with extreme caution in the sampling areas. Ammendolia et al. (2021), for example, avoided direct contact by collecting discarded PPE with a specialized metal stick equipped with a hand-held claw. Furthermore, the researchers wore PPE

Table 2
Summary of studies on the release of micro- and nano-plastics from personal protective equipment, particularly face masks and wipes.

Type of PPE	Sample collection	Experimental setup	QA/QC	Filter and pore size	Quantification and characterization	Abundance	Characteristics	Reference
Medical surgical face masks, disposal medical face masks, normal disposal face masks and N95 face masks; 18 brands from China (New and used)	Masks worn by students and staffs for one day prior to the experiment	Mask + 200 mL of deionized water on a rotary shaker at 120 rpm for 24 h	1. Three replicates 2. Equipment and lab utensils were pre-washed with DI water and covered with aluminum foil 3. Cotton masks and laboratory coats, and clean gloves were worn 4. Prefiltering of water used for experiment 5. Blanks were used and particles found in them were subtracted	Millipore mixed cellulose filter; 0.8 μm	VI and Raman spectroscopy	Used masks: 183.00 ± 78.42 particles/piece New masks: 1246.62 ± 403.50 particles/piece	Fiber and fragment; PP and PET; Green, orange, blue, pink, transparent, yellow, black, grey, and purple; 100 – 500 μm dominant, with range between < 100 and > 2000 μm	Chen et al. (2021a)
Sixteen surgical three-layer masks from Italy	Purchased by GLF S.A.S (Italy)	1. Ear strip and nose bridge were removed 2. A kitchen chopper was used for mechanical solicitation 3. 5 mL of each samples inspected for microplastics 4. 2 mL of each samples were treated with 30% H_2O_2	1. Beaker was washed with Milli-Q water for 5 times 2. Polystyrene yellow-green, fluorescent microspheres (0.1–1 μm) were used as reference reagents	–	VI, and flow cytometry	$0.3 \pm 0.1 \times 10^5$ items m^2 of fabric, overall, $2.6 \pm 0.5 \times 10^3$ items per mask	PP microplastics > 100 μm: 0.08–100 μm: $7.6 \pm 4.6 \times 10^8$ – $3.9 \pm 1.1 \times 10^{12}$ items per mask	Morgana et al. (2021)
Seven disposable surgical masks from Italy (New); Three-layer mask	Purchased online platform	1. UV light exposition by soaking in artificial seawater (ASTM D1141–98) under stirring for 10 hrs at 65℃; 18 times	1. Infrared spectra of nose strip and three layers of masks was taken prior to the analysis	Sieve: 500 μm stainless steel Whatman nitrocellulose filter; 0.45 μm	VI, SEM, and FTIR-ATR	No. of fibers mean: 117,400 ± 42,345 (mass loss of 0.07%)	Fiber and aggregate; 25–500 μm; PP	Saliu et al. (2021)
Disposable surgical mask from China (New masks)	Purchased from drug sales office	1. New mask in 3 L of ultrapure water under stirring for 24 h 2. Pre-washed masks in detergent solution (DS) sodium dodecyl benzone sulfonate and 75% alcohol disinfectant (DI) 3. Placed at the roof for aging of masks	1. Experiments were repeated three times 2. All glass instruments were cleaned with ultrapure water and alcohol 3. Cotton clothes all throughout experiments 4. Glassware pre-cleaned with 30% ethanol solution, rinsed with ultrapure water, then heat treated at 400 °C to remove organic impurities 5. Filters were cleaned with ultrapure water	Nitrocellulose membrane; 0.45 μm	VI, SEM, and micro-FTIR	1. Without DS and DI: 116,600 items per mask (mass loss: 0.47%) 2. -With detergent: 168,800 items per mask (mass loss: 1.14%) 3. With disinfectant: 147,000 items per mask (mass loss: 0.85%) 4. Microplastics release from aged masks: 6.0×10^8 – 6.4×10^8 items per mask	< 0.5–3.8 mm; 80% < 1 mm, Fiber; PP	Shen et al. (2021)
				–				

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Table 2 (*continued*)

Type of PPE	Sample collection	Experimental setup	QA/QC	Filter and pore size	Quantification and characterization	Abundance	Characteristics	Reference
Ecoparksg disposable masks (Canada)	Purchased from Fisher Scientific	1. Exposed to UV light (254 nm) for 1–48 h in a UV chamber 2. Outer, inner, and middle layer placed in 50 mL of water with sand (20 g) for 300 rpm and 25 °C for 36 h	1. Control samples wrapped in aluminum foil without UV exposure 2. Control experiments without mask in sand 3. Triplicates for each layer		SEM, FTIR-ATR, AFM, and in laser in-situ scattering & transmissometry analyzer	Without sand abrasion: 1.5 million microplastics per mask With sand abrasion: 16 million microplastics per mask	Fiber fragments, middle layer released greater microplastics; 10 – 250 µm; UV weathering: 30 – 100 µm	Wang et al. (2021)
New masks China	Purchased from drug stores or on-line shops, April- June 2020	Experiment I: 1. New masks in 100 mL of Milli-Q water shaken for 3 min for 10 times 2. 100 µL of leachate was placed on silicon wafer pretreated by ethanol Experiment II: 1. Nasal mucus was collected after 12 h of wearing masks using saline solution (5 mL of 0.9% NaCl); exposed for 30 s and 50 mg of mucus was collected 2. Filtered through 0.45 µm and passed through a 30% H_2O_2 and density separation ($ZnCl_2$) 3. Dye Pink staining 70°C for 2 h	1. Glass bottle previously burned at 500 °C for 4 h 2. A bottle without mask was used as a control 3. Triplicates were performed each batch of masks 4. A blank wafer was used as a control 5. Three replicates were performed for each scenario 6. Saline solution was checked under a microscopy for external contamination 7. Mucus collected from persons without wearing a mask 8. Microplastics on the filter transferred to glass vial and frozen	Aluminum oxide filter; 0.22 µm	SEM, AFM, and FTIR	Abundance: 2.8 – 6.0 × 10^9 per mask Mucus: 2.6 ± 0.4–10.6 ± 2.3 microplastics per mucus secretion	Middle layer releases large number of irregularly shaped particles; 5 nm to 600 µm < 1 µm particles were predominant Nasal mucus contained microplastics that can be inhaled while wearing a mask; larger than 1 mm are found and the number of particles varied with higher breathing frequency	Ma et al. (2021)
Seven common masks (Five-layer N95 respirator, surgical mask, cotton mask, non-woven mask, fashion mask, and activated carbon mask) China	–	Experiment I: Masks fixed tightly on top of the suction cup of vacuum pump -Milli-Q water was used to clean the suction cup, and the ejected microplastics were transferred onto the membrane via vacuum suction Experiment II: Microplastic inhalation risk using UV radiated, washed, disinfected masks for a period of 2 – 720 h	1. A blank test, a suction test without mask, and a test that only allows air to pass through the filter membrane were conducted. 2. Designed to reflect a realistic situation of microplastics inhalation and no contamination control measures were applied.	–	VI, LDIR, and Raman	Increase in microplastics with time exposure	Fiber and spherical type particles; 600–1800 µm	Li et al. (2021)
10 Disposable Face masks of 7 brands	Purchased from several manufacturers in China	Masks were submerged in 1.5 L deionized water	Procedural blanks with each batch by filtering 1.5 L of deionized water	Aluminum oxide filter; 0.1 µm	VI, SEM, and FTIR	–	Fiber; PP and PA, dye eriochrome black and congo red; < 25 µm –	Sullivan et al. (2021)

(*continued on next page*)

Table 2 (*continued*)

Type of PPE	Sample collection	Experimental setup	QA/QC	Filter and pore size	Quantification and characterization	Abundance	Characteristics	Reference
(new); colored plain, black		under agitation for 4 h					2.5 mm; black, blue, and pink	
Three wet wipes	–	1. Each sample was cut into 5 cm × 5 cm pieces 2. Experiment I 3. Rubbing wipes for 10 times on gloves and rinsed with 100 mL of DI water 4. Experiment II 5. Immersing wipes in water for 1 h 6. Experiment III 7. Dried wipes at oven were rubbed and followed the steps of experiment I 8. All collected samples were treated with H_2O_2	1. All experiments were conducted on a clean bench and stored in glass bottles 2. Petri dishes covered with aluminium foil 3. Procedural blanks with deionized water were conducted 4. Triplicates were carried out for each wipe	Anodisc filter; 0.2 µm	VI, FESEM, and FTIR	Experiment I: 180–200 p/sheet Experiment II: 693–1066 p/sheet	Polyester; Fiber, mostly cylindrical smooth shape; 93% of fibers were more than 100 µm	Lee et al. (2021)

DI: Deionized water; VI: Visual Inspection; LDIR: Laser Direct Infrared Imaging; ATR-FTIR: Attenuated Total Reflection- Fourier-transform infrared spectroscopy; FESEM: Field Emission Scanning Electron Microscopy; AFM: Atomic Force Microscopy.

and frequently used hand sanitizer during the surveys to ensure their own safety. Another challenge is the safe preservation of collected PPE litter. This was accomplished by securely tying the samples and storing them in woven garbage bags, aluminum foil, or plastic bags for further analysis. In the case of citizen science programs, the volunteers taking part in the survey must be thoroughly instructed on all of the above-mentioned safety precautions to be followed throughout the survey and collection of PPE litter.

3.3. *Occurrence, abundance, and sources*

The most recent PPE surveys focused on a variety of environments, including streets nearby beaches and metropolitan areas (Canada and South Africa), river outlets (Indonesia), and coastal shorelines (Peru, Chile, Bangladesh, Persian Gulf, and Morocco) (Table 1). The lower number of studies could be attributed to the impact of the COVID-19 pandemic on local or global surveys. Nonetheless, thanks to the researchers who made the PPE pollution survey possible after the COVID-19 restrictions were relaxed, or even while the COVID-19 restrictions were in effect. The findings revealed that PPE litter was prevalent in all of the environments studied (Table 1). Face masks (disposable medical, N95 masks, cotton, sponge, and reusable), face shields, gloves, hazard suit material, and disinfectant wipes were among the numerous PPE items identified in the studies reviewed. According to all studies, face masks have never been seen in previous surveys. Face masks and disinfectant wipes were commonly encountered in all surveys (shoreline, street, and floating debris), accounting for more than half of total PPE debris (Table 1). Moreover, face masks accounted for 80 – 98% of all PPE types in a few studies conducted in Peru and Bangladesh (Rakib et al., 2021; De-la-Torre et al., 2021; Haddad et al., 2021). The reported PPE density varied by region of the world, which can be influenced by sampling methods, area sampled, region type (tourist or non-tourist), and COVID-19 restrictions, resulting in incomparable results. The PPE density found along Moroccan, Bangladesh, Peruvian, and Chilean coastal shorelines was 1.13×10^{-5} PPE m^{-2}, 7.44×10^{-4} PPE m^{-2}, 6.29×10^{-3} PPE m^{-2}, and 6.00×10^{-3} PPE m^{-2}, respectively (Haddad et al., 2021; Rakib et al., 2021; De-la-Torre et al., 2021; Thiel et al., 2021). Whereas the PPE density in Canadian and Kenyan streets was 0 – 8.22×10^{-3} PPE m^{-2} and 0 – 5.6×10^{-2} PPE m^{-2}, respectively (Ammendolia et al., 2021; Okuku et al., 2021). In addition, Thiel et al. (2021) analyzed the concentration of PPE in Chilean tourist beaches during the summer and winter seasons. The findings revealed a higher density of PPE in the summer (3 face masks km^{-1} d^{-1}) than in the winter (0.2 face masks km^{-1} d^{-1}), due to an increase in beach visitors and a lack of waste bins and littering signs. Alarmingly, there was a significant increase in the number of discarded PPE items in the post-lockdown period compared to the lockdown period on Morocco's beaches (Haddad et al., 2021).

Given the prevalence of face masks and wipes found in recent surveys, they are believed to be the result of poor waste management practices and a lack of environmental awareness among locals and beachgoers. There is evidence that tourism contributes more to beach PPE littering than fishing (Rakib et al., 2021; Thiel et al., 2021). The presence of PPE in coastal shorelines can be attributed to a lack of centralized guidance, particularly on tourism beaches, about where to discard used PPE, which has resulted in ineffective PPE disposal methods. PPE made of low-density polymers, such as polypropylene, polyethylene, and polyester, on the other hand, can float in water, travel long distances in the environment, and reach the shorelines. Despite methodological differences, the current literature strongly suggests that PPE litter has a greater impact on aquatic environments. These data also indicated an unprecedented prevalence and growth of PPE in plastic litter across a wide range of environments worldwide, contributing significantly more than originally understood to the ongoing plastic waste problem.

Table 3
Studies investigating the presence of chemicals in PPE leachates.

Type of mask	Sample collection	Experimental set up	Chemicals identified from leachates	Methodology	Instrument used	Levels	Reference
Surgical masks, Self-filtering masks – KN95, Self-filtering masks - FFP2, Self-filtering masks - FFP3, Filters for homemade masks, Reusable masks; 20 samples	Manufacturers in China, Spain and Germany	1. Airborne particulate matter in 2 paper-mache dummy heads was collected using a Personal Environmental Monitor with a flow rate of 10 L/min. 2. Each mask was tested for 6 h, for both indoor and outdoor.	Triethyl phosphate, triphenylphosphine oxide, tris(2-chloroisopropyl) phosphate, Tri-n-butyl phosphate, tris (1,3- dichloro-2-propyl) phosphate, triphenyl phosphate, diphenylcresyl phosphate, 2-isopropylphenyl diphenyl phosphate, tricresyl phosphate, bis(4-isopropylphenyl) phenyl phosphate, tris(2-isopropylphenyl) phosphate and tris(2-ethylhexyl) phosphate	1. Filters were cut and added with 25 ng of an internal standard mixture. 2. Hexane:acetone (1:1) were added to filters and sonicated. 3. Solvent was concentrated & redissolved with methanol to 500 µL	Thermo Scientific TurboFlow™ system consisting of a triple quadrupole (QQQ) MS	16.3 – 27,735 ng/mask	Fernández-Arribas et al. (2021)
Thirty-six different brands of single-use face masks, including six medical masks and 30 nonmedical masks	Local stores in Toronto, Canada, in 2021	–	Synthetic phenolic antioxidants: butyl-4-methylphenol, 2,4-di-tert-butyl-phenol, pentaerythritol tetrakis[3-(3,5-di-tert-butyl-4-hydroxyphenyl)-propionate], octadecyl-3-(3,5-di-tert-butyl-4-hydroxyphenyl) propionate, 1,3,5-tris[(3,5-di-tert-butyl-4-hydroxyphenyl) methyl]− 1,3,5-triazinane-2,4,6-trione Organophosphite antioxidants: tris(2,4-di-tert-butylphenyl) phosphite, tris(2,4-di-tert-butylphenyl) Phosphate, bis(2,4-di-tert-butylphenyl) pentaerythritol diphosphate, bis(2,4-di-tert-butylphenyl) pentaerythritol diphosphite	~0.04 g of sample was into small pieces after which three internal standards were added. -The sample was then extracted with 4 mL of methanol. -After centrifugation, 1 mL of the extract was transferred into an injection vial.	Liquid chromatograph coupled to a triple-quadrupole mass spectrometer	Synthetic phenolic antioxidants: 4.44 × 10^3 to 9.15 × 10^4 ng/g Organophosphite antioxidants: 1.55 × 10^4 to − 5.13 × 10^5 ng/g	Liu and Mabury (2021)
Disposable Face masks	Manufacturers in China	–	Metals: Cu, Cd, Co, Pb, Sb and Ti Caprolactam (PA 66 monomer) PEG derivatives (prevalent in all masks) PA6 trimer PA66 trimer or PA6 tetramer Aromatic pyrrole like compound Olumucine like compound N-Undecyl-1-undecanamine C21H47N2O8 C22H52O5N6Na	1. 10 face masks for each batch submerged in 1.5 L deionized water for 4 h and agitated. 2. Leachate was then filtered through 0.1 µm Al_2O_3 filter. 3. Filters dried for 2 h at 50 °C. 4. Metal analysis: leachate was acidified with 1 mL 1 M HNO_3 acid. 5. For polar organic compounds leachate was directly injected	Scanning Electron Microscope, Fourier-transform infrared spectroscopy, -Inductively coupled plasma mass spectrometry, -Liquid Chromatography and Mass-spectrometry	Metals (microgram L-1) Cd: 0.01 – 1.91 Co: 0.54 – 0.59 Cu: 0.85 – 4.17 Pb: 0.01 – 6.79 Sb: 1.06 – 393 Ti: 0.06 – 0.64	Sullivan et al. (2021)

(*continued on next page*)

Table 3 (*continued*)

Type of mask	Sample collection	Experimental set up	Chemicals identified from leachates	Methodology	Instrument used	Levels	Reference
				into liquid chromatography.			
Wet wipes	Families residing in the city of Guangzhou, South China	1. Hand wipes from a total of 45 adults and 30 children 2. Gauze pads soaked with isopropyl alcohol and used to wipe the entire surface of both hands. 3. Prior to sampling participants were told not to wash hands for at least 2 h & to fill out a questionnaire about their demographic and dwelling characteristics.	60 Plastic additives (PAs): Phthalates, Mono-phthalates, Non-phthalate plasticizers, UV stabilizers: benzotriazoles, benzothiazoles, benzophenones, Antioxidants, Organophosphate esters, and Bisphenols	1. Wipes were spiked with surrogate standards and extracted with 10 mL of methanol/water, 6 mL of acetonitrile, 6 mL of ACN/isopropanol, and 6 mL of hexane/isopropanol. 2. Target analytes were eluted out with 5 mL of ACN and 5 mL of methanol and concentrated.	1. Shimadzu HPLC coupled to AB Sciex 5500 Q Trap MS/MS 2. Agilent 7890B gas chromatography coupled to a 5977 A mass analyzer	ΣPAs: Adults: 650–87,030 ng Children: 1230 −19,360 ng	Chen et al. (2021b)

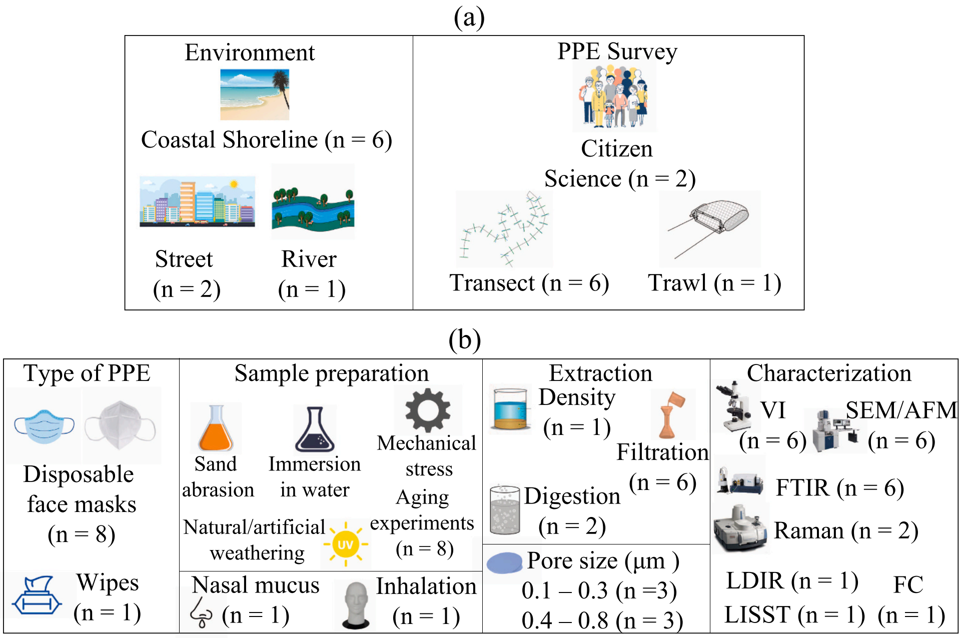

Fig. 1. A detailed analysis of the methodologies utilized to (a) explore PPE accumulation in diverse environments and (b) examine the degradation/fragmentation of PPE to micro- and nano-plastics. n: number of studies; VI: Visual inspection; FC: Flow cytometry; LDIR: LDIR: Laser Direct Infrared Imaging; ATR-FTIR: Attenuated Total Reflection- Fourier-transform infrared spectroscopy; LISST: Laser in-situ scattering and transmissometry analyzer; SEM: Scanning Electron Microscopy; AFM: Atomic Force Microscopy.

3.4. *Future opportunities*

Protocol standardization is required to ensure reliable, reproducible, and comparable results, along with a list of safety risk measures. More PPE surveys are urgently needed around the world in order to have a comprehensive data structure for understanding the magnitude and density of PPE pollution. More research on the occurrence of PPE in bottom marine sediments is needed because PPE made of high-density polymers like polyurethane and polyacrylonitrile can sink and light-density PPE may undergo biofouling processes that increase their density, allowing them to reach bottom marine sediments. Recent evidence demonstrates that PPE has a negative impact on wildlife through entanglement and ingestion (Gallo Neto et al., 2021; Silva et al., 2021), and more research into the effects of PPE pollution on organisms is required. Given that tourism activities are resuming in many parts of the world, PPE disposal should be strictly regulated, with specific waste bins installed for proper disposal of used face masks. Beach management programs must conduct educational campaigns to motivate locals and visitors to practice responsible behavior in terms of environmental governance and proper PPE disposal. Beach managers and sanitary workers must be cautious in separating collected PPE litter and transporting it to a designated location, such as a landfill or incineration plant. More importantly, we are concerned with the volume of waste that improper PPE disposal would generate during the post-covid19 pandemic, as there is a risk that people might take disposal for granted if PPE is of no longer useful. As a result, the government must develop new protocols based on environmentally sustainable practices for effective PPE collection and disposal.

4. PPE degradation and microplastics discharge into environment

4.1. Methodology

With the increase in marine PPE pollution during the pandemic, it is expected that any improperly discarded PPE will remain in the environment for years, contributing significantly to the plastics pollution, particularly micro- and nano-plastics. As a result, quantifying the micro- and nano-plastics release into the environment by PPE via fragmentation/degradation is considered critical. Laboratory studies, which mimic environmental conditions, are the most reliable way to assess and understand the mechanisms influencing the release ability of micro- and nano-plastics by PPE. As shown in Table 2 and Fig. 1b, researchers have adopted various strategies and characterization methods to address the PPE degradation features as well as the discharge of micro- and nano-plastics in the aquatic environment. Of a total of 9 studies, face masks have received the most attention ($n = 8$) in comparison to other PPE materials ($n = 1$; disinfectant wipes) due to their widespread production, use, and disposal. Face masks of various types, including medical surgical face masks, disposal medical face masks, normal disposal face masks, and N95 face masks with respirators, have been tested for micro- and nano-plastics release ability. The majority of studies ($n = 5$) focused on disposable face masks, which are the most common PPE found in the environment.

The three main steps in recent studies on microplastics release by PPE were: (1) sample preparation, (2) microplastics separation, and (3) quantification and characterization (Fig. 1b). Recognizing that PPE is subjected to various forms of fragmentation and weathering once it reaches the environment, researchers set out to recreate similar conditions in the lab. Thus, the first step in sample preparation was to subject the selected PPE either whole or in pieces, to a simulated experiment, which can include natural weathering, artificial aging under UV radiation/stirring, submerging in artificial seawater/distilled water/ultrapure water, washing with detergents and disinfectants, mechanical sand abrasion, and hand rubbing (in case of wipes). While many researchers used new masks/wipes purchased online, at a drug store, or from a manufacturer, only a few utilized used masks by asking volunteers to wear them for a period of time (Chen et al., 2021a). Prior to the analysis, the ear strip and nose bridge were removed in order to estimate the micro- and nano- plastics released by the face masks alone. Some researchers have even separated and weathered each layer of mask (outer, middle, and inner) to account for the amount of microplastics released (Ma et al., 2021; Wang et al., 2021). The weathering conditions, such as incubation time (1–48 h), temperature (25–65 °C), and stirring speed (e.g., 120 rpm), varied between studies. In addition, a few studies repeated the experiment ten to eighteen times to better understand the pattern of micro- and nano-plastics release from PPE. At the end of the experiment, the PPE was dried and weighed to determine how much mass had been lost due to fragmentation/degradation. Apart from the aging experiments, only one study collected nasal mucus from adult after wearing masks for 12 h to investigate the presence of micro- and nano- plastics using saline solution (Ma et al., 2021). In many studies, the microplastics released during the above-mentioned simulated experiments were separated directly through filtration. However, in some cases, the samples were digested with wet oxidant (e.g., H_2O_2) to remove organic impurities that were present (Ma et al., 2021; Lee et al., 2021). Following digestion, microplastics were separated by density using a $ZnCl_2$ salt solution and then separated from supernatant fluids via filtration (Lee et al., 2021). For microplastics separation, a variety of filter membranes with pore sizes ranging from 0.1 to 0.8 μm were used, including anodisc filters, aluminum oxide filters, mixed cellulose filters, and nitrocellulose filters.

Several methods are used to quantify (i.e., count) and characterize (i.e., morphology, size, and polymer type) the micro (nano) plastics released by PPE, which can have a significant impact on their reported size ranges and abundances between studies. Microplastics, for example, are frequently detected using a microscope with a size limit detection of 0.5 mm, while other methods for identifying micro- and nano-plastics included FTIR, Raman, LDIR, SEM-EDX, AFM, and laser in-situ scattering and transmissometry, all of which have various detection limits (from 20 μm to 0.1 nm).

4.2. QA/QC measures

Several precautionary measures have been established in the laboratory to avoid secondary contamination (e.g., airborne, dress) and limit overestimation of microplastics counts. All studies determining the release or degradation of PPE masks and wet wipes adhered to the QA/QC measures. Preliminary steps included maintaining a clean laboratory environment, as well as wearing cotton lab coats and clean gloves throughout the experiments. Except for the study by Li et al. (2021), in which the goal was to simulate a realistic situation of microplastics inhalation, the experiments were not conducted in a super-clean laboratory and no contamination control measures were used. All glassware used in experiments was pre-cleaned with Milli-Q, ultrapure, or deionized water, and in a few studies, heat treatment (400–500 °C) was used to remove organic impurities. Similarly, all solutions were pre-filtered to prevent contamination in the experimental analysis. Pre-cleaned metal tweezers were preferably used to recover the PPE samples submerged in water without having any contact with other materials (Shen et al., 2021; Morgana et al., 2021). The use of replicates, blanks, and control samples is critical for ensuring the quality of the analysis. Triplicates for each mask layer or batch/brand and wipes were conducted in the reviewed studies. Blank samples were used in these studies to identify secondary contamination from the laboratory (i.e., airborne) or from analytical procedures performed (i.e., equipment, filtering unit, solutions). Similarly, Wang et al. (2021) conducted control experiments without mask under the same analytical conditions as those with mask samples. Procedural blank samples prepared with deionized water ($n = 2$) were run with each batch of analysis. While, in the experimental study conducted by Li et al. (2021), a blank suction test without a mask was performed throughout the experiment, allowing only air to pass through the filter membrane. Also, covering the filter samples and instruments with aluminum foil with minimum exposure to air is highly recommendable. It is noteworthy that all of the studies used QA/QC measures, implying confidentiality in the results obtained.

4.3. Microplastic amount, characteristics, and causes

Various studies to date indicate that the release of micro- and nano-plastics is caused by a variety of factors. Mechanical abrasion while wearing, adjustment, folding, and pulling of the PPE, as well as breakage and fragmentation due to sand abrasion and UV weathering, are all examples (Han and He, 2021; Saliu et al., 2021; Shen et al., 2021; Wang et al., 2021). As seen in Table 2, all of the tested PPE (masks and wipes) degraded/fragmented into micro- and nano-plastics under various aging/environmental conditions, with concentrations reaching upto 6.0×10^9 per mask. Nonetheless, the release behavior of the masks differed before and after natural aging, indicating that the natural environment had an impact on the PPE (Shen et al., 2021; Saliu et al., 2021; Wang et al., 2021). Furthermore, we found a significant difference in the amount of microplastics released between surgical and nonwoven masks, which is most likely due to the fact that surgical masks have a middle layer made of melt-blown fabric, whereas nonwoven masks have all layers made of nonwoven fiber. For example, the discharge of micro- and nano-plastics from middle layer was greater compared to outer and inner layers (Ma et al., 2021; Wang et al., 2021). Thus, the type of masks used in the studies must be considered when comparing the total of microplastics released. Surprisingly, Li et al. (2021) uncovered that prolonged human exposure to masks results in small plastic particles inhalation from the mask itself. It was supported by the findings of (Ma et al., 2021), where nasal mucus from adults contained 2.6 ± 0.4–10.6 ± 2.3 microplastics per mucus secretion. Similarly, microplastics were found after rubbing wipes on the hand at a concentration of 180–200 particles per sheet (Lee et al., 2021), indicating yet another route of human plastic particle exposure.

Micro- and nano-plastics in a wide range of shapes are discharged from masks and wipes, including fibers, fragments, irregularly shaped clumps/aggregates, and spherical type, with fibers accounting for more than 80% of the total. They ranged in size from 5 nm to > 2000 μm, with the majority being particles larger than 100 μm. The size distribution was found to vary with aging process, layer in masks, and the type of PPE used (Table 2). Nevertheless, it is important to bear in mind that the disparity of methods used for separation, identification, and quantification of micro- and nano-plastics can also affect the comparability of the results between studies. The color of the particles differed depending on the type of mask. For example, Chen et al. (2021a) and Sullivan et al. (2021) found a variety of colored microplastics released from masks, including green, orange, blue, pink, transparent, yellow, black, grey, and purple. Polymers such as PP, PE, PET, and dye molecules such as eriochrome black and congo red were found during the polymer characterization. PP type micro- and nano-plastics were common among those reported, indicating an unprecedented increase in their ambient concentration with the ongoing COVID-19 pandemic.

These findings provided a strong foundation of what could happen to PPE in the environment and how humans are exposed to plastic particles through PPE use in daily life. If artificial weathering can cause fragmentation of face masks/wipes into millions of microplastics within a few days, it is possible that the gradual aging and decomposition of the entire masks in the environment increases the release, resulting in billions of micro- and nano-plastics having significant environmental impact and being immediately bioavailable to organisms.

4.4. Future opportunities

The current understanding of microplastics release by PPE is based on MilliQ, distilled, and deionized water, but it is critical to conduct similar research using other bodies of water, such as rivers and seas, as well as soil environments. Other than micro- and nano-plastics, PPE breakdown is also likely to be a source of mesoplastics (> 5 - < 25 mm) (Andrady, 2011), thus additional research is needed in this area. Reusable PPE has been the alternative during the pandemic's forewarning of the need to shift our single-use PPE practices. Even the Centers for Disease Control and Prevention (CDC) has recommended the use of reusable (i.e., washable) gowns made of polyester or polyester-cotton fabrics (CDC, 2021). There is currently no research into the potential release of microplastics in a variety of reusable PPE materials manufactured around the world, such as masks, gowns, hair coverings, and shoe covers. The release of microplastics should therefore be estimated for each kg of reusable or cleaned gowns washed. It is also clear that landfills and dumpsites are the most common destinations for plastic PPE waste in developing countries such as India, South Africa, and Mexico etc. Experiments involving the simulation of landfill conditions in the laboratory and the assessment of PPE degradation effects for the release of leachates are required. Future research must take note that the conditions of landfills and dumpsites vary depending on location, management, and waste characteristics. Finally, plastic wraps for face masks would be a source of pollution in the environment, and they deserve special attention and consideration. All of these should be taken into account when investigating the PPE consequences of micro- and nano-plastics pollution in the environment.

5. Organic and inorganic contaminants in PPE

5.1. Analytical methods

A few recent studies attempted to identify a variety of organic and inorganic contaminants that were intentionally or unintentionally added to PPE during production and assess their levels in various PPE manufactured around the world. Among the PPE tested were surgical masks, self-filtering masks, cloth reusable masks, homemade masks with disposable filters, and wipes for children and adults made in China, Vietnam, Mexico, Spain, Canada, and Germany, with products from China being studied the most in the studies reviewed (Table 3). They were purchased from the manufacturer, local stores, or were collected from nearby households. Furthermore, packaging materials were tested alongside masks because they can be a source of chemicals once they reach the environment. Initially, the entire PPE or pieces of it were transferred into glass vials with an internal standard. The samples were then extracted with a solvent mixture to obtain leachate and filtered or centrifuged to remove the particles prior to instrumental analysis (Table 3). For elemental analysis, the leachate can be acidified further with acids like Nitric Acid. To estimate the possibility of inhalation of plasticizers or additives by humans while wearing masks, Fernández-Arribas et al. (2021) conducted an experiment in which two paper-mache dummy heads representing an adult human's head were fitted with an anti-electrostatic inlet tube connected to a PM2.5 head to collect airborne particulate matter in microfiber filters using a Personal Environmental Monitor. For elemental analysis, ICP-MS and SEM-EDX are employed (Sullivan et al., 2021), whereas LC-MS, LC-UV, and HPLC-MS/MS are often used for identifying organic compounds (Chen et al., 2021b; Fernández-Arribas et al., 2021; Liu and Mabury, 2021).

5.2. QA/QC measures

Given the high sensitivity in detection of various chemicals associated with PPE materials, adhering to QA/QC measures in analysis is critical. Preferably, high grade chemicals and standards were used in the experiments. Main step in analyzing chemical leachates from PPE materials is extraction process using a solvent. Hence, it becomes extremely important to check the extraction efficiency. In this regard, Liu and Mabury (2021) randomly selected few samples to be extracted and analyzed again after the first extraction. The targeted chemicals were detected in the second extraction and never exceeded 5% of their corresponding concentrations in the first extraction, which they considered as sufficient extraction efficiency for the study. Furthermore, spiking/recovery tests are used to determine whether the value obtained from a sample is accurate or if there is an interfering factor in the sample matrix during measurement. This test involves "spiking" a known amount of chemicals into a sample and running it through the instrument. The resulting concentration of the spiked material also termed as “recovery”, clearly shows if the expected value of targeted chemical can be measured accurately. For instance, Liu et al., spiked two concentrations (1000 and 10,000 ng/g) of target chemicals in triplicate. In addition, non-spiked samples were analyzed alongside the spiked samples to check the background concentrations. The recoveries were in the range of 51−113% for the 1000 ng/g spiking level and 47−115% for the 10, 000 ng/g spiking level. Likewise, Chen et al. (2021b) spiked pre-cleaned gauze pads with target chemicals and processed with the same analytical procedures to evaluate recovery efficiencies. In a similar manner, all the studies performed spiking/recovery tests to ensure the accuracy of the chemicals measured by the instrument. Besides, reagent blanks, procedural blanks and control samples were also included when analyzing the PPE materials. In addition to the QA/QC measures mentioned above, Fernández-Arribas et al. (2021) used a field blank in their experimental setup. As their experiment involved the use of two paper-mache dummy heads with face masks, the blank consisted of a dummy head without wearing any face mask. Overall, by adhering to the QA/QC protocols outlined above, the studies ensured the accuracy and precision of the analysis.

5.3. *Identified compounds and their abundance*

The findings of the existing peer-reviewed studies confirmed that face masks and wipes include a wide spectrum of organic and inorganic pollutants used as plasticizers, UV stabilizers, and flame retardants in plastic production that include phthalates (di and mono) and non-phthalates, antioxidants, organophosphate esters, bisphenols, and plastic additives (Supplementary Material Table S2). It is worth noting that they were found in all of the samples tested, with at least one or more target chemicals identified. For example, organophosphate esters are common in all the PPE leachate tested irrespective of the manufacturer at concentration between 16.3 and 27,735 ng/mask, others included polyamide-66 monomer, oligomers (nylon-66 synthesis), surfactant molecules, dye-like molecules, and polyethylene glycol (Fernández-Arribas et al., 2021). Liu and Mabury (2021) found and described synthetic antioxidants in multilayered single use face masks at concentrations ranging from 2.00×10^4 to 5.75×10^5 ng/g, including synthetic phenolic antioxidants and organophosphite antioxidants. ICP-MS analysis also confirmed the presence of other leachable metals like cadmium (up to 1.92 μg/L), antimony (up to 393 μg/L) and copper (up to 4.17 μg/L) (Sullivan et al., 2021). Chen et al. (2021b) reported more than 60 plastic additives (phthalates, monophthalates), non-phthalate plasticizers, UV stabilizers (benzotriazoles, benzothiazoles, benzophenones), antioxidants, organophosphate esters, and bisphenols in adult and child hand wipes. Authors found the total mass of plastic additives in adults and children hand wipes ranged from 650 to 87,030 ng (median: 6110 ng) and 1230–19360 ng (median: 5600 ng). These findings highlight the importance of further research into human exposure pathways and potential health risks from the chemicals found in PPE. Given the hazardous nature, few countries have applied regulations for chemical additives in face masks from those framed for general products (e.g., AfPS GS 2019:01 PAK in Germany and EU REACH regulation), by and large, there is no specific regulation for organic compounds in face masks and there are several other chemicals yet to be investigated in PPE.

5.4. *Future opportunities*

According to the current review, there is a significant research gap in understanding chemical emissions from PPE degrading mechanisms (mechanical, chemical, and biological) and the exposure risks associated with them. Similarly, because the significant proportion of PPE is incinerated, analyzing the degradation products contained in smoke is critical. There is a lack of information on the types and concentrations of chemicals found in each layer of disposable face masks, as well as the nose strip, ear bridge, and respirators. Given that they could be a vector of organic and inorganic compounds, once they reach the environment, it is necessary to identify, characterize, and distinguish them, which is another area of research to be explored. Numerous products manufactured, used, and discarded in those unexplored country regions must be tested. We believe that there are many other chemical additive families that are yet to be identified and characterized, indicating the need for additional research on this topic. Furthermore, the release of metal nanoparticles found in antimicrobial face masks manufactured at COVID-19 pandemic during washing and reuse of the face mask into aqueous media must be evaluated. Aside from PPE, other items of plastic packaging and wraps that witnessed the increased production during the COVID-19 pandemic must be investigated to determine the levels of additives present.

6. PPE as a complex threat: exposure pathways and risks to environment and human health

PPEs from COVID-19 present significant challenges as a contaminant category due to their complexity, diversity, and limited studies in characterization, exposure pathways and assessment of toxicological hazards limits our understanding of true fate of PPEs. It is becoming clear that PPEs contribute to the world's already significant levels of macro-, meso-, micro-, and nano-plastics pollution as well as, to a variety of other contaminants ubiquitous in the environment (Fig. 2). The accumulation of PPE litter, like any other plastic waste, poses a number of risks to the environment, animal health, and human health (Fig. 3) (Silva et al., 2021). Recently, there is a scientific record of mortality of marine species, a juvenile Magellanic penguin, directly linking to the ingestion of a protective mask (Gallo Neto et al., 2021). The micro- and nano-plastics, especially fibers, released from PPE litter as a result degradation and fragmentation would be harmful to a variety of organisms upon accidental ingestion. Our recent review analysis emphasized that in terms of effects, microfibers are significantly more toxic and may have potential impact than microbeads on organisms of different habitats (Kutralam-Muniasamy et al., 2020). According to available scientific evidence, nanoplastics are formed after ingestion of microplastics released from PPE by terrestrial organisms (earthworm *Eisenia andrei* and springtail *Folsomia candida*) via biofragmentation (Kwak and An, 2021), which then end up in feces polluting the environment. In case of humans, the prolonged use of facial masks has shown to cause several skin problems like irritant contact dermatitis (Aerts et al., 2020). At the same time, micro- and nano-fibers can be transmitted from the face masks and enter the respiratory track via hand to mouth contact, inhalation or dermally absorbed (Han and He, 2021; Li et al., 2021). If inhaled, the body may not remove these particles rapidly enough to prevent lung damage. A recent study found polymeric plastic fibers ranging in size from 8.12 to 16.8 μm in human lungs, pointing to inhalation as a possible route of microplastics to humans (Amato-Lourenço et al., 2021). As a result of this situation, we are concerned that health care workers who frequently wear masks may be exposed to numerous micro- and nano-plastics.

Micro- and nano-plastics are well-known to sorb and concentrate contaminants from surrounding environment, imposing risks of transfer of contaminants in organisms across different trophic levels including humans. Not only the contaminants from environment but the release of chemical compounds (e.g., plasticizers, flame retardants and metals) found in PPE themselves (Fig. 2) are a cause of concern for environment and human health. It is important to note that most of them are ubiquitous in the environment and characterized as toxic (Hahladakis et al., 2018; Wang et al., 2020). For example, organophosphate esters (OPEs) have been observed to disrupt endocrine and reproductive functions,

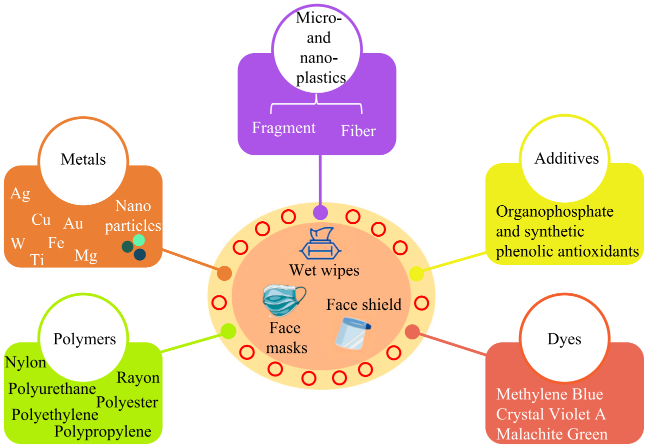

Fig. 2. An overview of known contaminants associated with PPE.

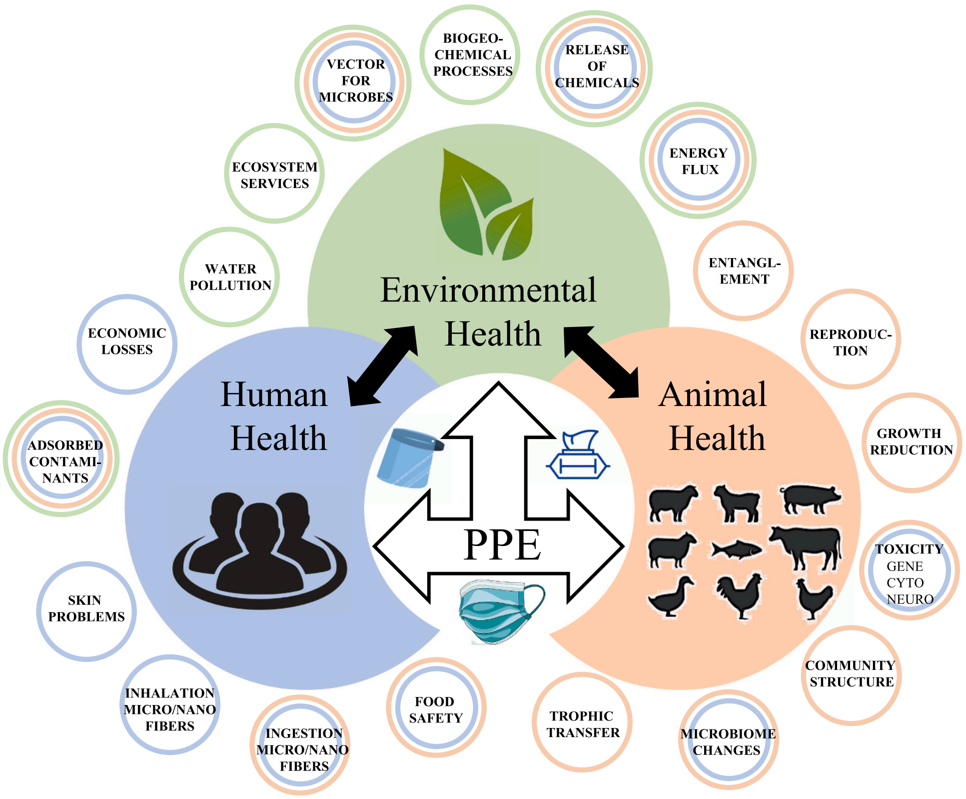

Fig. 3. Potential effects of PPE on the environment, animal, and human health.

nervous system development decline of semen quality and are also associated with asthma and allergies (Meeker and Stapleton, 2010; Pantelaki and Voutsa, 2020). Thus, wearing certain types of face masks for long periods of time could result in potentially hazardous chemicals and micro- and nano-plastics being inhaled deep into human lungs. Additionally, these chemicals may dissolve in moisture droplets of sweat and saliva, which may act as a medium for transport into the body. It is critical to determine the extent of any negative effects on humans from PPE use. To find answers, few researchers estimated an approximation of human exposure to several chemical compounds such as synthetic antioxidants (AO), synthetic phenolic antioxidants (SPA), organophosphite antioxidants (OPA), and organophosphate esters (OPE). Fernández-Arribas et al. (2021) estimated daily intake value for OPEs in mask via inhalation and reported the values ranging between 0.02 and 39.6 ng/kg bw/day. Similarly, Liu and Mabury (2021) calculated daily intakes of synthetic phenolic antioxidants and organophosphite antioxidants, and their sum up ranges were 0.24−4.16 ng (kg of body weight)$^{-1}$ day^{-1} for adults dermal exposure. Even OPEs have been detected in hand wipes and their estimation for hand to mouth and dermal exposure were 2.7 × 10−3–42 ng/kg bw/day for adults and 0.13–1340 ng/kg bw/day for children. The carcinogenic and non-carcinogenic risks were also evaluated for these chemicals and were far below the threshold safe levels. Based on these findings, we can conclude that these chemical compounds are unlikely to pose significant health risks and are safe for humans to use; however, continued exposure could be hazardous. Moreover, data for toxic thresholds for a wide range of chemicals are still lacking, making accurate estimation of chemical-dependent exposure risks difficult. In addition, while all of the studies determined individual chemical exposure levels, the combined effects of a mixture of chemicals present in PPE materials on exposure remains unidentified. Thus, the evidence regarding the potential health risks posed by the wide range of chemical compounds used as additives, flame retardants, and plasticizers is inconclusive at this time.

In contrary, chemicals applied during production or absorbed in the environment can remain and bioaccumulate in wildlife, with trace quantities released into the environment accumulating over time and contaminating the food chain. Because the majority of used PPE in developing countries is landfilled due to a lack of infrastructure, we are concerned about the amounts of additives and monomers released from PPEs as they breakdown in landfill conditions. They leach into our soil and groundwater over time, posing environmental hazards for years. For example, about 90% of plastic waste in South Africa ends up in landfills (Olatayo et al., 2021). Here, we attempted to estimate the amount of chemicals that would most likely be released in landfills using the assumption that 10% of all daily used face masks are landfilled (Table 4). In this regard, the median concentrations measured in the studies of Liu and Mabury (2021), Chen et al. (2021b), and Fernández-Arribas et al. (2021), were adopted. According to our estimates, global environmental exposure levels correspond to tons of chemicals per year, implying that discarded PPE materials, as well as their degradation products meso-, micro-, and nano-plastics, are a source of numerous chemicals to the environment. We believe this will have a significant environmental impact, and as a result, landfill leachate should be closely monitored for the presence of plastic particles and chemicals. Though the estimates in Table 4 highlight a new environmental threat, it is also important to consider chemical stability under the environmental conditions we are simulating (in landfill), the half-life (degradation) of the chemical compounds, and other factors when evaluating chemical release from PPE.

7. Conclusion

We must recognize now that COVID-19-related plastics waste is an unavoidable byproduct of the pandemic's adaptive process. PPE, particularly face masks, pose a global environmental challenge of our time, and have sparked scientific interest in determining their effects on both the environment and human health. The review presented here is a first step toward a more systemic, cross-scale, and multi-disciplinary

Table 4
An approximation of chemical sources in landfills associated with 10% face masks used.

Country	Total population	Face mask acceptance (%)	Daily mask usage	Organic compound ng d^{-1}			
				SPA[a]	OPA[a]	AO[a]	OPE[b]
Bangladesh	169,775,000	63	1069,582.5	1155,149,100	6588,628,200	7487,077,500	36,633,200.63
China	1424,548,000	84	11,966,203.2	12,923,499,456	73,711,811,712	83,763,422,400	409,842,459.6
Indonesia	27,223,000	78	212,339.4	229,326,552	1308,010,704	1486,375,800	7272,624.45
India	1383,198,000	80	11,065,584	11,950,830,720	68,163,997,440	77,459,088,000	378,996,252
Vietnam	98,360,000	91	895,076	966,682,080	5513,668,160	6265,532,000	30,656,353
Sri Lanka	21,084,000	80	168,672	182,165,760	1039,019,520	1180,704,000	5777,016
Philippines	109,703,000	90	987,327	1066,313,160	6081,934,320	6911,289,000	33,815,949.75
Thailand	69,411,000	86	596,934.6	644,689,368	3677,117,136	417,8542,200	20,445,010.05
Myanmar	54,808,000	80	438,464	473,541,120	2700,938,240	3069,248,000	150,17,392
Pakistan	208,362,000	68.8	1433,530.56	1548,213,005	8830,548,250	10,034,713,920	49,098,421.68
Malaysia	32,869,000	87	285,960.3	308,837,124	1761,515,448	2001,722,100	9794,140.275
Japan	126,496,000	83	1049,916.8	1133,910,144	6467,487,488	7349,417,600	35,959,650.4
South Korea	25,841,000	84	217,064.4	234,429,552	1337,116,704	1519,450,800	7434,455.7
Norway	5450,000	23	12,535	13,537,800	77,215,600	87,745,000	429,323.75
Russia	143,787,000	60	862,722	931,739,760	5314,367,520	6039,054,000	29,548,228.5
United Kingdom	67,334,000	71	478,071.4	516,317,112	2944,919,824	3346,499,800	16,373,945.45
Spain	46,459,000	95	441,360.5	476,669,340	2718,780,680	3089,523,500	15,116,597.13
Sweden	10,122,000	5	5061	5465,880	31,175,760	35,427,000	173,339.25
France	65,721,000	88	578,344.8	624,612,384	3562,603,968	4048,413,600	19,808,309.4
Germany	82,540,000	69	569,526	615,088,080	3508,280,160	3986,682,000	19,506,265.5
Italy	59,132,000	94	555,840.8	600,308,064	3423,979,328	3890,885,600	19,037,547.4
Greece	11,103,000	80	88,824	95,929,920	547,155,840	621,768,000	3042,222
Ireland	343,000	83	2846.9	3074,652	17,536,904	19,928,300	97,506.325
Finland	5580,000	52	29,016	31,337,280	178,738,560	203,112,000	993,798
Denmark	5797,000	62	35,941.4	38,816,712	221,399,024	251,589,800	1230,992.95
Netherland	17,181,000	75	128,857.5	139,166,100	793,762,200	902,002,500	4413,369.375
Belgium	11,620,000	85	98,770	106,671,600	608,423,200	691,390,000	338,2872.5
Portugal	10,218,000	87	88,896.6	96,008,328	547,603,056	622,276,200	3044,708.55
Romania	19,388,000	87	168,675.6	182,169,648	1039,041,696	1180,729,200	5777,139.3
Saudi Arabia	34,710,000	83	288,093	311,140,440	1774,652,880	2016,651,000	9867,185.25
Iran	83,587,000	64	534,956.8	577,753,344	3295,333,888	3744,697,600	18,322,270.4
UAE	9813,000	88	86,354.4	93,262,752	531,943,104	604,480,800	2957,638.2
Nigeria	206,153,000	90	1855,377	2003,807,160	11,429,122,320	12987,639,000	63,546,662.25
South Africa	58,721,000	78	458,023.8	494,665,704	2821,426,608	3206,166,600	15,687,315.15
Turkey	83,836,000	82	687,455.2	742,451,616	4234,724,032	4812,186,400	23,545,340.6
Israel	8714,000	78	67,969.2	73,406,736	418,690,272	475,784,400	2327,945.1
USA	331,432,000	73	2419,453.6	2613,009,888	14,903,834,176	16,936,175,200	82,866,285.8
Canada	37,603,000	78	293,303.4	316,767,672	1806,748,944	2053,123,800	10,045,641.45
Argentina	45,510,000	85	386,835	417,781,800	2382,903,600	2707,845,000	13,249,098.75
Brazil	213,863,000	50	1069,315	115,4860,200	6586,980,400	7485,205,000	36,624,038.75
Chile	18,473,000	86	158,867.8	171,577,224	978,625,648	1112,074,600	5441,222.15
Colombia	50,220,000	88	441,936	477,290,880	2722,325,760	3093,552,000	15,136,308
Australia	25,398,000	32	81,273.6	87,775,488	500,645,376	568,915,200	2783,620.8
New Zealand	4834,000	70	33,838	36,545,040	208,442,080	236,866,000	1158,951.5
Mexico	133,870,000	82	1097,734	1185,552,720	6762,041,440	7684,138,000	37,597,389.5
Costa Rica	5044,000	87	43,882.8	47,393,424	270,318,048	307,179,600	1502,985.9
Kazakhsthan	18,794,372	80	150,354.976	162,383,374.1	926,186,652.2	1052,484,832	5149,657.928
Oman	5115,955	80	40,927.64	44,201,851.2	252,114,262.4	286,493,480	1401,771.67
Kuwait	4275,450	80	34,203.6	36,939,888	210,694,176	239,425,200	1171,473.3
Singapore	5854,053	80	46,832.424	50,579,017.92	288,487,731.8	327,826,968	1604,010.522
Bahrain	1705,531	80	13,644.248	14,735,787.84	840,48,567.68	95,509,736	467,315.494
Armenia	2963,706	80	23,709.648	25,606,419.84	146,051,431.7	165,967,536	812,055.444
Afghanisthan	38,992,638	80	311,941.104	336,896,392.3	1921,557,201	2183,587,728	10,683,982.81
Nepal	29,176,450	80	233,411.6	252,084,528	1437,815,456	1633,881,200	7994,347.3
Lebanon	6822,802	80	54,582.416	58,949,009.28	336,227,682.6	382,076,912	1869,447.748
Maldives	541,266	80	4330.128	4676,538.24	26,673,588.48	30,310,896	148,306.884
Hong Kong	7501,879	80	60,015.032	64,816,234.56	369,692,597.1	420,105,224	2055,514.846
Taiwan	23,820,377	80	190,563.016	205,808,057.3	1173,868,179	1333,941,112	6526,783.298
Cambodia	16,736,949	80	133,895.592	144,607,239.4	824,796,846.7	937,269,144	4585,924.026
Global Environmental Exposure per day				**49,501,826,227**	**2.82344E+11**	**3.20845E+11**	**1569,849,582**

SPA: Synthetic phenolic antioxidants; OPA: Organophosphite antioxidants; AO: Synthetic antioxidants; OPE: Organophosphate esters; a: Study results of Liu and Mabury (2021); b: Study results of Fernández-Arribas et al. (2021); Face mask acceptance rate adopted from Chowdhury et al. (2021).

understanding of impacts of PPE in the ecosystem, as it provides a thorough assessment of recent advances and strategies for PPE research across several disciplines, as well as possible implications. The amount of PPE research is slowly accumulating and showcases the importance of focusing on the steps required to comprehend all the possible environmental repercussions. Recent evidence suggests that the widespread prevalence of PPE wastes is already exacerbating plastic pollution in seas, streets, and rivers, making them likely impossible to eliminate. There are no simple solutions to this complex problem; however, we can try to hinder its progress through education campaigns involving the general public, scientific researchers, and governmental organizations in order to improve proper disposal and waste management. As seen in this review, actively developed tools by researchers have increased the amount of data obtained from PPE on various aspects and assisted in bridging the knowledge gap between modeling and experimentation. Traditional microplastic research methods, in particular microscopy, density separation, SEM, FTIR, and Raman, used in limited studies on disposal face masks and wipes, have garnered novel insights into the discharge of micro- and nano-plastics in the environment. The evidence gathered from the literature also highlights the potential of the available analytical techniques, which will undoubtedly fuel further PPE research and development and serve to meet future needs. To date, the majority of research has focused on single-use face masks, but there are still potentially unexploited opportunities, as described in Sections 3.4, 4.4, and 5.4. Moreover, the risks of man-made chemicals in PPE to the environment and human health are poorly understood, and current knowledge, particularly for long-term exposures, is inadequate. We can be certain of one thing: while wearing face masks helps to prevent the spread of COVID-19, it does not prevent humans from inhaling microplastics, to which they also contribute. Moving forward, on the research side, ecotoxicology assessment, sorption-desorption characteristics, and chemical hazard identification are more important than ever in identifying and mapping the most relevant risks involved in the interactions between PPE-associated pollutants and organisms. Although much remains unknown about PPE, researchers have answered many questions about how improperly disposed PPE can be a source of micro- and nanoplastics, as well as a vector of numerous chemicals, establishing a new era of microplastics research. And it became evident that, if not managed properly, these PPE may cause significant harm to organisms. In the future, we anticipate an increase in research from various topics discussed in order to develop rigorous evidence and gain a better understanding of the negative effects of PPE.

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. Supporting information

Supplementary data associated with this article can be found in the online version at doi:10.1016/j.jhazmat.2021.126945.

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