Science of the Total Environment 786 (2021) 147628

Contents lists available at ScienceDirect

Science of the Total Environment

journal homepage: www.elsevier.com/locate/scitotenv

Face mask waste generation and management during the COVID-19 pandemic: An overview and the Peruvian case

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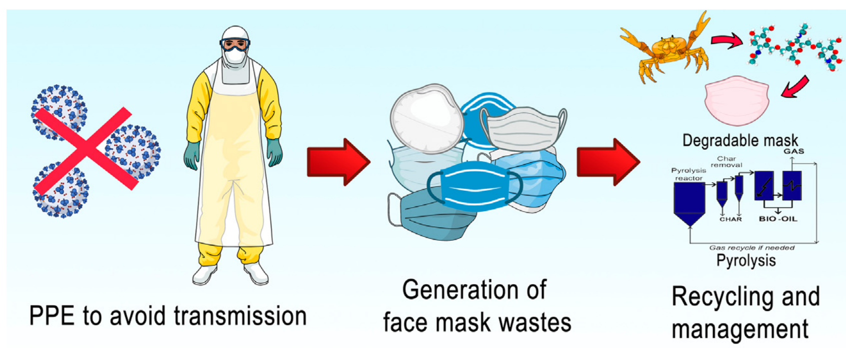
HIGHLIGHTS

- Face masks are the most widely used and discarded personal protective equipment.
- Biodegradable masks are promising alternatives to reduce their impact.
- Polypropylene in face masks can be recycled by mechanical or thermal means.
- Face mask waste generation was calculated for Peru.

GRAPHICAL ABSTRACT



ARTICLE INFO

Article history:
Received 11 March 2021
Received in revised form 1 May 2021
Accepted 2 May 2021
Available online 8 May 2021

Editor: Damia Barcelo

Keywords:
Protective equipment
PPE
Surgical mask
Solid waste
Pollution
Environment

ABSTRACT

The ongoing COVID-19 pandemic has driven massive consumption of personal protective equipment (PPE) worldwide. Single-use face masks are one of the most used PPE to prevent the transmission of the virus. However, mismanagement of such materials threatens the environment with a new form of plastic pollution. Researchers argue that it is necessary to develop and implement innovative ways to manage and recycle PPE in order to reduce their impacts on the environment. In the present work, we have reviewed and discussed the recent development of sustainable face mask alternatives and recycling and repurposing routes under the COVID-19 pandemic context. Moreover, we have conducted estimations of the daily face mask waste generation in Peru, a developing country struggling with a poor solid waste management framework and infrastructure. Unlike previous studies, our equation incorporates the "economically active population" variable in order to provide more precise estimations, while evaluating single-use and reusable scenarios. The scenarios of incorporating reusable face masks significantly reduced the amount of solid waste generated in Peru. In situ evidence shows that face masks are polluting the streets and beaches of Peru, probably driven by mismanagement and poor environmental awareness.

1. Introduction

Plastic materials have become an essential part of modern society. Since the start of their mass production, the demand and manufacturing of plastic products have increased continuously (Geyer et al., 2017). In the latest report by PlasticsEurope (2020), it was reckoned that plastic production increased from 359 million tons in 2018 to 368 million tons in 2019. Poor solid waste management or incorrect disposal allows plastic wastes to become a ubiquitous contaminant (Corcoran et al., 2017), which may persist for long periods of time due to their low biodegradability (Andrady, 2017). Upon reaching the environment, plastic

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https://doi.org/10.1016/j.scitotenv.2021.147628
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materials interact with the biotic and abiotic parts, leading to physical changes, such as size and shape, and causing detrimental effects in organisms (Cole et al., 2011; Derraik, 2002).

For decades, it has been known that large plastic debris, referred to as macroplastics, may cause entanglement with marine species or be ingested by top predators, such as mammals, reptiles, and birds (Battisti et al., 2019; Poeta et al., 2017; Staffieri et al., 2019), thus severely affecting their wellbeing and potentially causing premature deaths (Wilcox et al., 2018). Moreover, most plastics are positively buoyant and subject to surface currents after entering the ocean (Hidalgo-Ruz et al., 2012; Shim et al., 2018). The long transport of fouling organisms across the ocean could turn plastics into vectors of non-native and invasive species (De-la-Torre et al., 2021a; Kiessling et al., 2015; Rech et al., 2018). Another widely investigated form of plastic pollution, namely microplastics (plastic particles smaller than 5 mm), derive from the breakdown of large plastic items, while others are manufactured in micro-sizes (De-la-Torre et al., 2020; Eriksen et al., 2018). Due to their smaller size, microplastics are prone to ingestion by a larger number of organisms from different taxa (Garcés-Ordóñez et al., 2020; Ory et al., 2018, 2017; Santillán et al., 2020). The possible uptake routes can be active (confusion with natural prey or food source) or passive (accidental ingestion while feeding, filtering, or breathing, depending on the feeding behavior) (Roch et al., 2020). Additionally, microplastics are known to leach toxic chemicals and carry sorbed contaminants (Holmes et al., 2012; Rochman et al., 2014; Torres et al., 2021). Upon ingestion, microplastics can induce sublethal ecotoxicological effects in most organisms (Aragaw and Mekonnen, 2021a). In organisms at the lowest trophic levels, such as microalgae *Microcystis aeruginosa*, common polyvinyl chloride (PVC), polystyrene (PS), and polyethylene (PE) microplastics inhibit growth and induce oxidative stress (Zheng et al., 2021). Co-exposure of MPs to *Danio rerio* (zebrafish) in the early stages of development leads to neurotoxicity, oxidative stress, and behavioral changes (Santos et al., 2020). Moreover, the capacity of microplastics to bioaccumulate and biomagnify across the food web turns them into potential threats to food security and human health (De-la-Torre, 2020; Miller et al., 2020).

The COVID-19 pandemic that the world is currently facing has sparked a large demand for single-use plastic products (Alfonso et al., 2021). Among these, the use of personal protective equipment (PPE), such as face masks, face shields, and gloves, has tremendously increased as an efficient way to prevent the transmission of the virus (De-la-Torre et al., 2021b). Silva et al. (2020) argue that the pandemic has compromised the legislative progress against single-use plastics while recycling programs have stopped due to the risk of transmission (Zambrano-Monserrate et al., 2020). Additionally, most governments enforce the use of PPE in public places, which poses a challenge to conventional waste management and could severely exacerbate plastic pollution (Akhbarizadeh et al., 2021; Ardusso et al., 2021; Prata et al., 2020). In a recent review by Hiemstra et al. (2021), photographic evidence of fish entrapment and bird entanglement with PPE was reported, along with a list of reports of glove and facemask ingestion by urban and domestic animals. Additionally, it has been demonstrated that disposable face masks are able to leach chemical contaminants and microfibers to the environment under experimental conditions (Sullivan et al., 2021). Indeed, pollution with PPE could cause long-term effects on the marine environment (Aragaw, 2020; De-la-Torre and Aragaw, 2021; Fadare and Okoffo, 2020).

Amidst the sudden increase in the use of PPE, various studies have estimated the consumption of face masks, the most used type of PPE, in urbanized areas. For instance, Boroujeni et al. (2021) estimated the daily face mask use in Victoria, Australia, reached 5,351,520 masks day^{-1} under a single-use scenario. On the other hand, highly populated countries, like India and China, could reach a daily face mask use estimated in the hundreds of millions (Sangkham, 2020). In Peru, a recent study has evaluated the occurrence and distribution of PPE in coastal environments of the overpopulated city of Lima, most of which were regarded as surgical face masks (De-la-Torre et al., 2021b). Implementing organized beach clean-ups is regarded as an efficient way to preserve the ecological and economic value of coastal areas (Battisti et al., 2020). However, these types of conservation actions may be impacted by lockdown restrictions due to the ongoing pandemic.

Surgical masks are mainly composed of polypropylene (PP), thus turning them into a source of fossil plastic and microplastic pollution (Aragaw, 2020). However, the current generation of face mask wastes and the implications of solid waste management to prevent marine pollution remain unknown. Hence, in the present work, the current alternatives and innovative management of face mask plastic wastes under the context of the ongoing COVID-19 pandemic were reviewed. We aimed to provide a brief guide for researchers and decision-makers about the various alternatives to minimize the impact generated by the COVID-19 pandemic and to state research priorities. Additionally, we conducted a case study of Peru, a country with poor waste management plans and infrastructure, based on the generation of face mask wastes under different scenarios to estimate the magnitude of this issue in developing countries.

2. Materials and methods

2.1. Literature search

In April 2021, a literature search was conducted aiming to retrieve articles and documents related to the management of face mask wastes and sustainable alternatives. The ScienceDirect (https://www.sciencedirect.com/) and Scopus (https://www.scopus.com/) databases were consulted for this matter with the keywords “Face mask” or “PPE” or “personal protective equipment” in conjunction with “waste”, “reusable”, “sustainable”, “biobased”, “recycling”, or “LCA”. Results were limited to the years 2020–2021, as most of the literature related to solid waste management under the COVID-19 context was published in these two years. The references of the retrieved articles were consulted if necessary. Additionally, articles estimating the generation of solid wastes associated with the use of face masks were retrieved too.

A total of 444 documents were obtained from the last two years, including those from the scholarly databases and reference search. Initial article screening was based on their aims and scope. Opinion or review articles with no experimental design were excluded. Articles focused on the current COVID-19 pandemic context were of special interest. For the second screening, studies were required to conduct experimental or technical procedures to evaluate 1) the development of biodegradable masks or respirators, 2) thermochemical conversion of masks for energy recovery, or 3) unconventional recycling routes. Additionally, the studies reported estimations of mask waste generation (at a local or national level) were retrieved. Thirteen records evaluating biodegradables alternatives or recycling routes and 10 records estimating face mask generation were retrieved.

2.2. Estimation of face mask waste generation

Regions are the first level of administrative division in Peru, subdivided into several provinces. There are 24 regions in Peru and the Constitutional Province of Callao (“Callao” from now on), which is an independent province. The number of daily face mask generation (DFM) was calculated for each of the 24 Peruvian regions and Callao based on the equation proposed by Nzediegwu and Chang (2020) with modifications:

$$DFM = (T_p \times U_p \times A_{r1} \times A_c \times E_p) + (T_p \times U_p \times A_{r2} \times A_c \times (1 - E_p))$$

where T_p is the total population of the region, U_p is the percentage of urban population in the region, A_{rx} is the percentage of face mask acceptance rate, A_c is the estimated daily face mask use per capita, and E_p is the economically active population. In contrast with the equation originally used by Nzediegwu and Chang (2020), the present makes a distinction between the daily face mask use of the population considered as economically active (EAP) and those who are not. The EAP is technically defined as the people who are currently employed or actively looking for a job (even if unemployed). This variable was introduced to the equation in order to make more precise estimations regarding face mask use and waste generation based on the assumption that non EAP are less likely to leave their homes. In Peru, the use of face masks is mandatory in public places and outdoors. However, a certain percentage of the urbanized population stay at home without the need to use masks (Götz et al., 2021). Hence, considering only the EAP, our estimations focus on those who are constantly leaving their homes and required to use face masks during the day. A global online survey by Chang et al. (2020) demonstrated that the prevalence of mask-wearing in South American countries was high (>85%). The surveys were collected off Facebook app, in which more than 70% of the users are in the range of 18 to 44 years old (Chen, 2021). Considering this information, along with the current enforcement of mask use in public places by the government, the variable A_{r1} was determined to be 80%, assuming this value may be representative of the EAP. As of April 2021, there are no ongoing strict lockdowns (with the exception of specific holidays) and most businesses, such as restaurants, casinos, supermarkets, and malls, are open to the public with limited capacity. Hence, the variable A_{r2} was assumed to be 40%, representing the population not belonging to the EAP.

The Department of Operational Support of the United Nations recommends the use of non-medical fabric/cloth masks for the general public (UN, 2020). However, a recent report of PPE pollution in coastal areas in Peru found that at least ~67% of the masks were single-use, demonstrating the preference for surgical and N95 masks by the Peruvian population (De-la-Torre et al., 2021b). Hence, four scenarios of face mask use per capita were evaluated. Assuming a scenario based on only single-use face masks, A_c was determined as 1 mask per day per person, and three additional scenarios considering the use of reusable face masks were evaluated, where A_c was determined as 0.2, 0.1, and 0.05 masks per day per person, for masks that are 5, 10, and 20 times reusable. The demographic and general information of the 24 Peruvian regions and Callao and the variables are displayed in Table 1.

Table 1
List of the 24 Peruvian regions and Callao, their total population, percentage of urban population, and assumed variables.

Region	T_p[a]	U_p (%)[a]	E_p (%)[a]	A_{r1} (%)	A_{r2} (%)	A_c (mask day^{-1} person^{-1})
Amazonas	426,806	41.5	53.6	80	40	0.05, 0.1, 0.2, 1
Ancash	1,180,638	63.4	49.8			
Apurímac	430,736	45.8	53.1			
Arequipa	1,497,438	91.8	49.0			
Ayacucho	668,213	58.1	51.1			
Cajamarca	1,453,711	35.4	52.1			
Cons. Prov. Callao	1,129,854	100	56.2			
Cusco	1,357,075	60.7	46.3			
Huancavelica	365,317	30.5	57.6			
Huánuco	760,267	52.1	55.5			
Ica	975,182	92.4	51.2			
Junín	1,361,467	71	67.0			
La Libertad	2,016,771	78.9	55.3			
Lambayeque	1,310,785	81.1	61.3			
Lima	10,628,470	83.1	49.0			
Loreto	1,027,559	68.7	62.3			
Madre de Dios	173,811	82.8	57.4			
Moquegua	192,740	86.9	51.9			
Pasco	271,904	63.1	56.0			
Piura	2,047,954	79.3	63.3			
Puno	1,237,997	53.8	59.0			
San Martín	899,648	68.1	62.4			
Tacna	370,974	90.1	57.5			
Tumbes	251,521	93.7	49.0			
Ucayali	589,110	81	76.5			

[a] Data retrieved from the population growth estimations based on the last census reported by the National Institute of Statistics and Informatics (INEI). The links to the species documents are available in Table S1.

Maps were performed in ArcGIS 10.7 and graphs were created using GraphPad Prism.

3. Alternatives, technologies, and waste management

3.1. Bio-based face masks

Biopolymer research has gained great interest on behalf of the scientific community due to its biocompatibility, biodegradability, and eco-friendliness (Shen et al., 2020; Torres and De-la-Torre, 2021). Their LCA environmental performance will vary depending on the selection of biopolymer and production processes. However, biopolymers are generally less impacting than fossil-based plastics in categories associated with resource scarcity and toxicity (Rojas-Bringas et al., 2021; Saibuatrong et al., 2017). Hartanto and Mayasari (2021) applied an analytic hierarchy process to evaluated different materials for the development of eco-friendly non-medical masks. It was found that quilt and cotton 600 TPI were the best materials in terms of protection and lowest environmental impact index. However, no biomaterials were considered in their analysis. Most studies tailor the physical and chemical properties of biopolymers and biocomposites to achieve improved and optimized materials for multiple applications (Ccorahua et al., 2017; Gómez et al., 2006). Some biopolymers are able to form micro- and nano-fibrous structures (Kikionis et al., 2015; Toskas et al., 2011), similar to those in face masks and filters.

The concept of bio-based masks to face the massive amount of non-degradable wastes produced during the COVID-19 pandemic was first highlighted by Das et al. (2020b) while proposing the suitability of wheat gluten nanofibers membranes as developed in their previous studies (Das et al., 2020a, 2019). The working mechanism of face masks can be summarized into electrostatic attraction or physical sieving. In electrostatic attraction, filters are made of charged materials that attract and retain oppositely charged particles, while physical sieving is divided into interception, inertial impaction, and diffusion mechanisms, where the blocked particles are >600 nm, 300–600 nm, and <300 nm in diameter depending on their pore size, respectively (Tebyetekerwa et al., 2020). In a later research, Choi et al. (2021) developed a Janus membrane filter based on the biodegradable polymer polybutylene succinate (PBS) coated with chitosan nanowhiskers (Fig. 1a). PBS-microfiber and nanofiber mats were prepared by electrospinning and assembled together (Fig. 1b). The outer microfiber layer was coated with positively charged chitosan, which allowed for electrostatic attraction to take place. Additionally, the inner nanofiber layer (fiber diameters of 0.51 μm and pore size of 3.5 μm) physically sieved the remaining particles (Fig. 1c). The performance of the filter was comparable to commercial N95 filters and was able to remove 98.3% of $PM_{2.5}$.

He et al. (2020) fabricated a biodegradable mask filter by electrospinning polylactic acid (PLA) and 3D printing the same material on top with a mesh arrangement. The electrospun fibers were 0.83 μm in diameter, pore size in the range of 0.58–0.81 μm, and exhibited a tensile strength ranging from 51.76 to 60.18 MPa depending on the nozzle temperature. The materials were able to filter up to 79 wt% of air at median mass aerodynamic diameter (MMAD) of 500–600 nm, which is higher than the standard for surgical face masks (55 wt% at 700 nm MMAD). Rather than mask filters, Chowdhury et al. (2021) fabricated a whole mask based on electrospun licorice roots mixed with polyvinyl alcohol (PVA). The fibers were 15–30 μm in diameter and contained micropores with high air permeability. Although the characteristics of this mask were tested preliminarily, it is discussed that the active compounds in licorice roots, 18-β glycyrrhetinic acid, and glycyrrhizin, have shown antiviral activities (Tong et al., 2020; Wang et al., 2015), which could give additional protection to the wearer, although further testing is required. Lastly, Vaňková et al. (2020) 3D printed PLA rigid structures to be used as respirators. Since respirators are expected to be reused several times, the microstructure of the 3D PLA prints was evaluated after disinfection with ethanol, isopropanol, or sodium

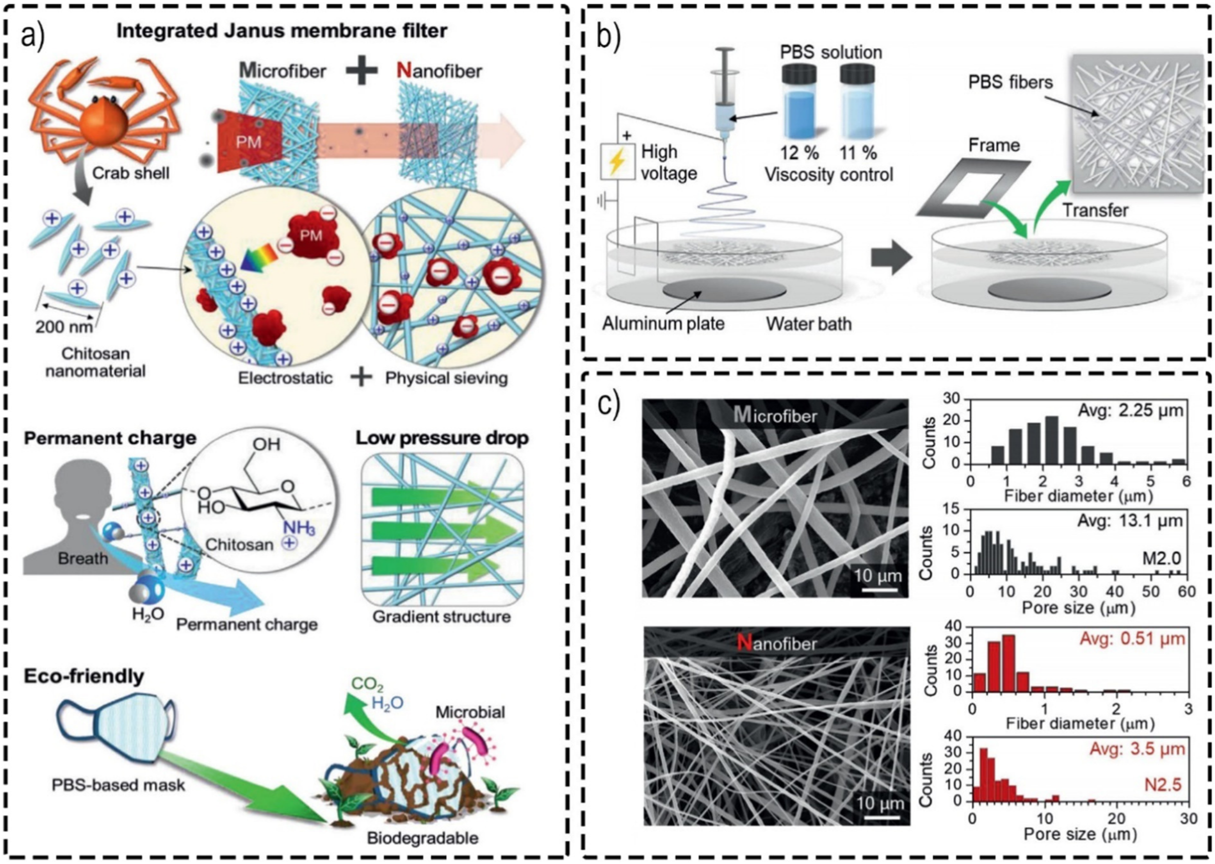

Fig. 1. a) Schematic representation of the chitosan nanowhiskers-coated PBS filter working mechanism and disposal, b) production process of the PBS filters by electrospinning, and c) SEM images of the microfiber and nanofiber PBS layers fabricated by electrospinning, along with the mean and distribution of the fiber diameters and pore sizes in both cases. Reprinted from Choi et al. (2021). Copyright (2021) with permission from Wiley-VCH.

hypochlorite. It was found that, apart from effectively eliminating various artificially inoculated bacterial, fungus and viruses, the PLA structures were not compromised. PLA is recommended as a suitable material for the manufacturing of this type of respirator. Currently, several enterprises have developed commercially available face masks based on sugar cane waste, coffee, and hemp fibers (Selvaranjan et al., 2021). Researchers argue that it is necessary to shift towards sustainable materials, such as PPE based on biopolymers (Patrício Silva et al., 2021).

Face masks are treated as a potentially contaminated material, thus specific disposal recommendations are given by the government or health organizations, such as sealing used face masks in plastic bags (Sangkham, 2020). These rules are no exception for different types of materials, and compromises the incorporation of biodegradable face masks to sustainable recycling routes, like composting (Hottle et al., 2017). Regardless, bioplastics are generally less impacting than fossil-based materials (Kakadellis and Harris, 2020). Since PLA is mostly produced from starch-rich crops, like cassava (Chiarakorn et al., 2010), large-scale production would require significant pressure on the agricultural sector. Additionally, the costs of common biobased and biodegradable polymers generally surpass those from conventional plastics (PE, PP, PET, and PS) (Shogren et al., 2019), while the market for biobased facemasks is largely unknown. Due to these logistical and economic constraints, the production of biodegradable face masks may be limited to small sectors or niche markets.

3.2. Energy recovery

Pyrolysis is the thermochemical decomposition of materials at high temperatures (>300 °C). Through this process, the low energy density materials are separated into gas fuels, high-density liquids (biofuel), and solids (biochar) (Sharma et al., 2014). Pyrolysis is an interesting disposal alternative to landfilling and for plastic wastes, including those from medical use (Al-Salem et al., 2017; Qin et al., 2018), without the need for material-based segregation (Demirbas, 2004). Jain et al. (2020) proposed that PPE kits associated with the COVID-19 pandemic could follow a repurposing strategy based on pyrolysis and the production of biofuels. They argue that due to the high polypropylene (PP) content in medical PPE (mainly surgical face masks), these could produce great yields of liquid and gas fuels, as seen in previous studies with PP wastes (Ahmad et al., 2015; Martynis et al., 2019). Recent studies have evaluated this method for the conversion of COVID-19-associated PPE into sustainable fuels. Jung et al. (2021) pyrolyzed a KF94 grade face mask in a tubular reactor to obtain gaseous fuels. In a first one-stage experimental setup, the reactor operated at temperatures from 35 to 600 °C (constant heating rate of 10 °C min^{-1}); in the two-stage setup, a second furnace was incorporated (operating at temperatures from 200 to 600 °C at 10 °C min^{-1} heating rate); lastly, a catalytic setup was evaluated using Ni/SiO_2 (5 wt% Ni) as a catalyst in the two-stage pyrolysis setup. The single-stage non-catalytic stages produced syngas and C_{1-2} hydrocarbons in low concentrations (<0.6 mol%), although the two-stage setup increased these values to 3.5 mol% of H_2, 12.0 mol% of CH_4, 4.8 mol% of C_2H_6, and 9.5 mol% of C_2H_4. Catalytic pyrolysis substantially increased the concentration of gas fuels, especially for H_2, which increased up to 55.1 mol%. Aragaw and Mekonnen (2021b) pyrolyzed face masks (mainly PP) and surgical gloves (PVC) in a reactor at 400 °C for 1 h. The recovery rate was ~75 wt% of crude oil and 10 wt% char. The quality and composition of the pyrolysis products were not measured. The yields were in similar orders of magnitude than previous experiments with plastic solid wastes (Fakhrhoseini and Dastanian, 2013; Mastral et al., 2002). Although the research of plastic waste conversion into sustainable liquid and gaseous fuels have been around for over a decade, those focusing on medical PPE under the COVID-19 context remain preliminary. Given the massive amounts of PPE waste generated, specially from face masks, it is necessary to find new ways to repurpose or recycle this material (Zand and Heir, 2021). In this sense, fuel recovery by pyrolysis seems like a promising alternative.

The technologies presented in the studies consulted remain in development (laboratory stage). Regardless, surgical and N95 masks can be treated as regular PP materials. The business feasibility of producing fuel from plastic waste has been evaluated by Fahim et al. (2021). The modeled capacity was determined as 13,000 tons of fuel out of 20,000 tons of waste (although this conversion ratio may vary depending on the dominant polymer types in the wastes). Almost 100% of the investment costs are attributed to the necessary equipment for large-scale pyrolysis, which is estimated at around 127,000 USD. The process starts with the collection and shredding of plastic feedstocks, which are then introduced to the pyrolysis reactor with a catalyst (550 °C at 5 °C min^{-1} heat rate) to produce oil and gas vapors. These products are condensed to produce different types of fuel oils and hydrocarbons. Lastly, biofuels are converted into gasoline and diesel in oil refineries. A notorious logistical benefit of this process is the lack of intensive plastic segregation efforts (Moreira et al., 2017). Based on this, Ghodrat et al. (2019) argue that plastic waste can be collected, transported, delivered by local authorities as part of their solid waste treatment plans, instead of investing in collection and selection processes. Pyrolytic conversion of scrap tires is a well-established alternative use of this technology for solid waste recycling (Oliveira Neto et al., 2019). Big enterprises in developed countries are considering shifting to this source of fuel and partnering with large-scale companies specialized in waste pyrolysis (Neumair, 2020), which may be a viable recycling stream for plastic PPE and PP face masks.

3.3. Innovative recycling and repurposing

Additional to fuel recovery, studies have investigated less conventional ways to recycle face mask wastes. For instance, Saberian et al. (2021) evaluated the suitability of using shredded face masks (SFM) along with recycled concrete aggregate intended for road base and subbase applications in the field of civil engineering. Results indicated that at 1 wt% of SFM, the aggregate showed the highest compressive strength (216 kPa) and resilient modulus (314.35 MP). The stiffness and strength exhibited by the blends under 1, 2 and 3 wt% SFM satisfied the requirements for pavement base and subbase applications, demonstrating their viability as sustainable base/subbase additive material. In a later study, the influence of surgical mask PP fibers (2 cm long and 0.5 cm wide) on the mechanical properties of concrete formulations was evaluated (Kilmartin-Lynch et al., 2021). The compressive strength, tensile strength, and ultrasonic pulse velocity increased in 17.1%, 12.2%, and 4.1%, respectively, after the addition of 0.2% (by volume of concrete) PP fibers. On the other hand, Young's modulus was highest (30.95 GPa) by adding 0.25% PP fibers.

Regarding advanced electrochemical applications, Hu and Lin (2021) treated surgical face masks to transform PP material into cathodes for supercapacitors. Face masks were collected from recycling sites and autoclaved at 110 °C for 12 h with H_2SO_4. Dried samples were then mixed with KOH at different mass ratios and activated at 750 °C for 2 h (heat rate of 5 °C min^{-1}) in a tubular furnace. The pH of the resulting black powder was normalized and dried. The material showed a maximum S_{BET} porosity of 2220 m^2g^{-1}. Also, the electrochemical measurements demonstrated outstanding specific capacity (328.9 F g^{-1} at 1 A g^{-1}), and power and energy density (300 W kg^{-1} and 11.2 W h kg^{-1}, respectively), which are comparable to those from previous research on plastic waste-based electrodes (Deka et al., 2020; Liu et al., 2020). Battegazzore et al. (2020) conducted multiple morphological, chemical, physical, and thermal analyses of mechanically extruded surgical face masks (separated into face mask, ear loop, and nose wire) in order to identify potential recycling routes. Prior analysis, face mask layers were cut in small squares and earloops 10 mm pieces and extruded at 190 or 230 °C, pelletized, and subject to hot compression molding at 180 °C or 230 °C for 2 min, resulting in thin films. Following their results, it is suggested that the extruded face mask material could be directly recycled by injection molding or complement its mechanical properties with fillers from agro-industrial wastes. In the case of earloops, the material could be used in injection molding but will exhibit lower mechanical properties. One drawback of recycling earloops is their heterogeneous polymer composition. Pietrelli et al. (2017) proposed a recycling scheme for marine plastic litter which may be suitable for PP and PE items, including PPE. The process consists of plastic collection, washing and density separation from PVC and sand, and re-extrusion (150–160 °C) with the addition of plasticizers. Energy recovery through pyrolysis was also suggested as a recycling alternative.

Since the recycling alternatives in this section require prior selection and handling of face mask materials, it must be noted that discarded face masks are likely to be contaminated. Hence, disinfection techniques are required before introducing used PPE material to a recycling stream. Schwartz et al. (2020) described the use of a Bioquell Clarus™ C system to decontaminate N95 respirators with H_2O_2 vapor. The procedure is carried out in a room designed for this matter, where H_2O_2 vapor is uniformly dispersed by the system, and suitable for large-scale decontamination. A similar procedure is described by Holdsworth et al. (2021), in which a low-temperature plasma vaporized H_2O_2 sterilization is used for reprocessing N95 respirators. The drawback of this technique is the limited number of respirators (10 per cycle) that can be processed simultaneously. Another less specialized alternative for the inactivation of the virus is exposing PPE items directly to the sun (Efstratiou and Tzoraki, 2021). This method could present a time constraint (~5 h for inactivation) and require extensive disinfection spaces on a large scale (Banerjee et al., 2021).

Contrary to pyrolytic degradation of plastic wastes, the less conventional forms of face mask recycling presented in this section, namely concrete subbase additive, mechanical recycling, and advanced electronics, require both segregation and disinfection of the materials. This will not only pose logistical constraints to successfully achieve a feasible recycling stream but also increase the costs of production. To the best of our knowledge, there are no large-scale business feasibility analyses of these types of recycling alternatives, probably because their development is still in the first stages. Some plastic extruding companies reprocess plastic waste through a twin-screw extrusion process (Moore, 2020). However, the heterogeneous composition of most face masks may set important drawbacks to the incorporation of this type of material. Technical studies must be accompanied by economic analysis and scale-up prospects in order to have a better understanding of their implementation cost and viability.

4. Face mask waste generation in Peru

The overall daily face mask waste generation for the entire country reaches 14,983,383.4 masks day^{-1} under a single-use scenario. Considering that a common surgical mask weighs 5 g on average, this number of face masks translates into roughly 74.9 tons of plastic waste daily (27,344.7 tons per year), out of which ~10% reaches the oceans (Avio et al., 2017). However, other studies estimate that a single-use surgical face mask may weigh about 3.68 g (Haque et al., 2021), 30 g (Boroujeni et al., 2021), or range from 2.5 to 10.58 g (Benson et al., 2021b). Lima contributed to 36.2% (5,427,236.0 masks day^{-1}) of the total waste generation, greatly surpassing La Libertad, the second-highest waste producer (974,370.3 masks day^{-1}). The results for each region are listed in Table S2. The highly variable percentage of urban population among regions along with the total population are important predictors of the estimated waste generation. Fig. 2 visually compares the total population and daily mask waste based on the single-use scenario.

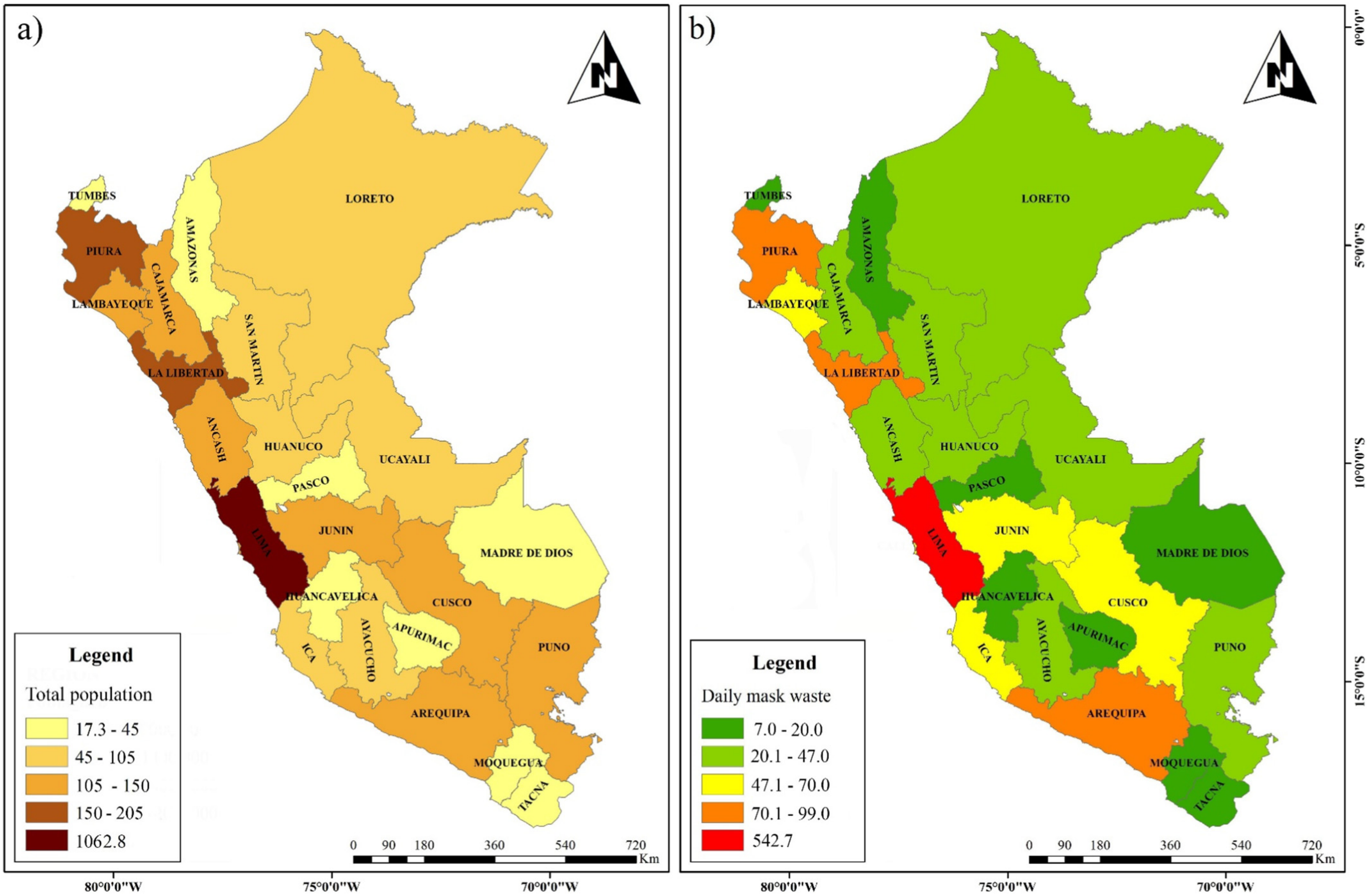

Fig. 2. Map of the Peruvian regions displaying a) the total population (×10,000) and b) daily mask waste generation (×10,000) based on the single-use scenario.

By varying the assumption of 1 daily face mask per capita to lower values, the resulting waste generation lowers proportionally (Fig. 3). Under the $A_c = 0.2$, the total number of face masks generated lowers to 2,996,676.7 masks day^{-1} (ranging from 15,729.3 to 1,085,447.2 masks day^{-1}) and for $A_c = 0.05$, 749,169.2 masks day^{-1} are generated (ranging from 3932.3 to 271,361.8 masks day^{-1}). The results for each region at different A_c values are displayed in Table S2. Reusable materials not only reduce the amount of waste generated but also exhibit a lower environmental burden from an LCA point of view (Ahamed et al., 2021; Civancik-Uslu et al., 2019). LCA studies agree that by

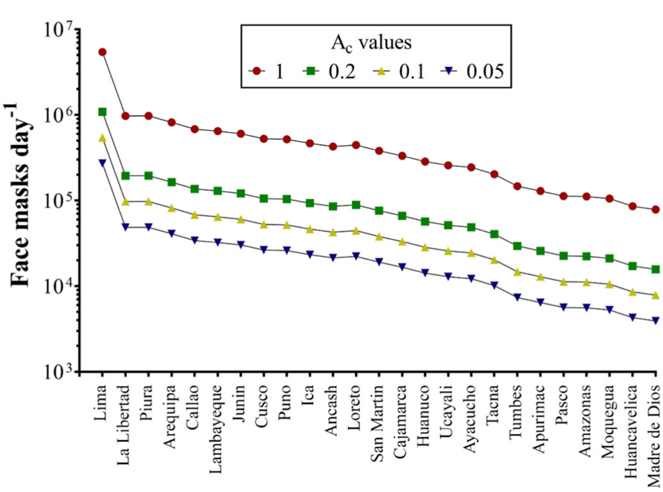

Fig. 3. Daily face mask waste generation for each region under four A_c scenarios. A_c: Daily face mask per capita.

extending the life of a plastic product (more reuses), their LCA impact categories display lower affectation to the environment. For instance, the emission of greenhouse gases during the production of common face masks raises to 0.05 and 0.59 kgCO_2 eq. per single-use N96 and surgical mask, respectively (Klemeš et al., 2020). On the other hand, the impact of reusable cloth masks on climate change becomes lower under the assumption of a higher number of reuses (Allison et al., 2020). The use of cloth/fabric masks by the general public is recommended by the Department of Operational Support of the United Nations (UN, 2020), as well as the Peruvian Ministry of Health (MINSA, 2021). However, it is unknown whether the Peruvian population is shifting towards reusable cloth masks. From our previous studies (De-la-Torre et al., 2021b) and personal observations (Fig. 4), it is apparent that single-use face masks are predominantly found polluting coastal environments and streets of urbanized cities. This is probably because single-use masks are generally cheaper and more accessible than cloth masks.

Additionally, we carried out in situ qualitative observations of discarded face masks polluting the streets and beaches of the Lima, Ancash, La Libertad, and Piura Regions (Fig. 4). These observations evidence face mask waste mismanagement in these two cities and suggests that these wastes have already reached coastal or marine environments. PPE has become a new significant source of marine plastic pollution, being evidenced in various beach sites in Latin America (Ardusso et al., 2021), and Africa (Okuku et al., 2020). In the case of Peru, solid waste management plans reach only 42% of the national territory (Gilardino et al., 2017). Currently, there are 55 infrastructures for solid waste disposal or landfills across the country, out of which only 9 (four located in Lima) are certified for this purpose (MINAM, 2020). Due to the lack of appropriate landfills in many urbanized and non-urbanized areas across the country, open dumpsites or locally known

Fig. 4. Photographs of surgical face masks polluting the streets and beaches of Piura, Ancash, La Libertad, and Lima Regions.

"botaderos" are used to dispose solid wastes without the necessary infrastructure to prevent environmental pollution and human health hazards (Walmsley et al., 2018). Importantly, the regions of Tumbes, Lambayeque, Madre de Dios, Arequipa, Moquegua, and Tacna lack access to any kind of waste disposal infrastructure (MINAM, 2020) and rely on illegal dumpsites or inefficient transportation of solid waste.

Solid waste management conditions in Peru present significant challenges to the implementation of novel and sustainable recycling routes for common face masks at a national level. However, some alternatives may be suitable to implement on smaller scales. For instance, several small businesses currently produce sugarcane bagasse food containers in Peru as sustainable alternatives to EPS. Sugarcane bagasse is a highly abundant residue from the extraction of sugarcane juice (Rabelo et al., 2015). It is mainly composed of cellulose, hemicellulose, and lignin, and exhibits a versatile micro-fibrous structure (Parameswaran, 2009). Given the micro-structure and abundance of sugarcane bagasse in Peru, we hypothesize that this material may be suitable for the production of biodegradable face masks or filters on a small scale. Importantly, the technical performance and filtering efficiency must be first evaluated under controlled conditions to assure the protection of the consumers. As of now, there are no businesses dedicated to the large-scale thermochemical transformation of plastic wastes through pyrolysis. However, the feasibility of implementing a pyrolysis plant for scrap tires has been evaluated with promising results in logistical and economical terms (Ramirez Velarde et al., 2018). Moreover, local authorities recently implemented a small pyrolysis plant (300 kg of capacity) in the Historic Sanctuary of Machu Picchu with looks to a carbon-neutral touristic destination (El Peruano, 2020).

Compared to other studies, the overall results estimated for Peru remain relatively low, considering that focusing on the economically active population almost halves the total estimation. For instance, Nzediegwu and Chang (2020) initially estimated the daily face mask generation using their proposed equation in 15 African countries, considering an 80% of face mask acceptance rate and 2 daily face masks per capita. The daily face mask generation ranged from 6,584,207 face masks day^{-1} in Niger to 171,508,139 face masks day^{-1} in Nigeria. Like in our results at a national level, face mask generation was correlated with the total population and influenced by the proportion of the urbanized population in a lower level. Haque et al. (2021) estimated the daily face mask waste for 11 selected countries, which were in the order of India > Indonesia > Nigeria > Pakistan > Bangladesh > Iran > France > The Philippines > South Africa > Ukraine > Kazakhstan and ranging from ~8.7 to ~386.4 million face masks day^{-1}. It should be noted that the estimation for Nigeria reached ~85.8 million face masks day^{-1}, about half of what was estimated by Nzediegwu and Chang (2020), mainly due to the difference in the daily face masks per capita number. A more comprehensive study by Benson et al. (2021a, 2021b) carried out the estimations for 57 African countries considering 1 daily face mask per capita and a 70% acceptance rate. It was found that Nigeria (75,036,504 face masks day^{-1}), Egypt (30,805,013 face masks day^{-1}), The Democratic Republic of the Congo (28,836,895 face masks day^{-1}), Ethiopia (16,900,032 face masks day^{-1}) and Tanzania (15,470,682 face masks day^{-1}) were the highest contributors to plastic waste associated to face masks. The 57 countries together amount to over 12 billion face masks every month, which translated to about 105,000 tons of waste. Akber Abbasi et al. (2020) carried out estimations for seven countries in the Arabian Peninsula, considering acceptance rates from 50 to 90% and the daily number of masks per capita from 1 to 4. The resulting daily face mask generation was in the order of Saudi Arabia > Yemen > The United Arab Emirates > Oman > Kuwait > Qatar > Bahrain. Sangkham (2020) estimated the daily face mask generation and medical waste (based on the number of COVID-19 cases and a medical waste generation rate) in 49 Asian countries. As expected, the most populated countries were the highest produced of face mask wastes, with China at the top (989,103,299 face masks day^{-1}), followed by India (381,179,657 face masks day^{-1}), Indonesia (159,214,791 face masks day^{-1}), Bangladesh (99,155,739 face masks day^{-1}), Japan (92,758,754 face masks day^{-1}), and Pakistan (61,762,860 face masks day^{-1}). In all of the countries together, it was estimated that medical waste generation could reach up to 16,659.48 tons day^{-1} under the COVID-19 pandemic. Urban and Nakada (2021) estimated more than 85 million face masks were generated in 30 cities across Brazil (state capital cities and cities with more than 1 million people), considering 2 daily masks per capita and 80% of acceptance rate. Benson et al. (2021a) estimated a total of 380,414,703 face masks day^{-1} for South America and specifically 19,535,824 face masks day^{-1} for Peru, which exceeds our estimations in about 4.55 million masks day^{-1}. Other studies aimed for focalized geographic areas, including the cities of Tehran and Isfahan in Iran (Zand and Heir, 2021, 2020) and Victoria, Australia (Boroujeni et al., 2021).

The main limitation of the present estimation relies on the arbitrariness of the selection of certain variables, such as face mask acceptance rate and daily face mask use per capita. These values are determined based on assumptions due to the lack of primary information, such as surveys. For instance, Nigeria was evaluated by Nzediegwu and Chang (2020), Haque et al. (2021), and Benson et al. (2021a, 2021b), all of them showing different results because different assumptions were taken for those two variables. Moreover, the behavior towards face mask use may vary across countries and cultures. The non-urbanized population is utterly excluded from the estimation, which could underestimate a significant number of face masks that are assumed to be less frequent in these areas. Regardless, this is a first estimation of the potential face mask waste generation during the ongoing COVID-19.

5. Conclusion

In the present article, we reviewed and discussed sustainable alternatives to single-use face masks, the most used type of PPE in the current context, and innovative alternative for recycling and repurposing this material. Recent research showed promising bio-based and fully degradable filters for reusable face masks with improved filtering effectiveness. Although some bio-based face masks are currently available in the market, these are significantly lower than conventional surgical and N95 masks. It is necessary to fully understand their implications from a cradle-to-grave LCA point of view before scaling bio-based PPE towards a larger market. Since several environmental impacts in biodegradable materials are partly compensated through a correct end-of-life choice, such as composting, a great barrier for developing countries with poor solid waste management is created. Moreover, face masks are treated as hazardous wastes and recommended by various health authorities to be disposed with extreme care, such as encasing or sealing the material. This presents a risk to the supply of biodegradable face masks to composting piles. Thermochemical transformation of plastic wastes through pyrolysis has also been proposed as a suitable alternative to recycle face masks. Prior waste segregation is not needed in this process, and various large-scale businesses already operate with scrap tires to produce biofuels. Other less conventional forms of repurposing or recycling face masks wastes require time-consuming and high-cost pretreatments, including disinfection and segregation of the plastic materials. It is necessary to focus on successfully implementing a circular economy of the massive amounts of PPE and single-use plastics produced in the context of the COVID-19 pandemic. Also, technical studies must be accompanied by feasibility and scale-up evaluations to determine the suitability of implementing such processes.

We conducted a case study of face mask waste generation in Peru by modifying and employing a widely used equation. We propose that incorporating the EAP variable into the equation would provide more precise estimations based on the assumption that EAP would leave their homes more regularly. Overall, face mask generation in Peru is fairly limited in contrast with highly populated countries. Despite having poor solid waste management plans across the country, some of the recycling and biobased alternatives may be suitable for implementation on a small scale. Additionally, we presented some personal records of face mask pollution in the streets and beaches of various Peruvian cities. In highly polluted sites with limited intervention from local authorities, operational efforts, such as beach clean-ups carried out by citizens, along with educational workshops may be a plausible solution to promote cleaner environments. Long-term measures, including in post-pandemic scenarios, should develop environmental awareness and education in the population, especially in countries that lack appropriate waste management infrastructure.

CRediT authorship contribution statement

Fernando G. Torres: Conceptualization, Formal analysis, Resources, Supervision, Project administration. **Gabriel E. De-la-Torre:** Investigation, Writing – original draft.

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.

Acknowledgments

The authors would like to thank the Vice-Rectorate for Research of the Pontificia Universidad Catolica del Peru (VRI-PUCP) for financial support. The authors are thankful to the anonymous reviewers for their constructive comments and suggestions.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.scitotenv.2021.147628.

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