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Rethinking and optimising plastic waste management under COVID-19 pandemic: Policy solutions based on redesign and reduction of single-use plastics and personal protective equipment

Ana L. Patrício Silva [a,*], Joana C. Prata [b], Tony R. Walker [c], Diana Campos [a], Armando C. Duarte [b], Amadeu M.V.M. Soares [a], Damià Barceló [d,e], Teresa Rocha-Santos [b]

[a] Centre for Environmental and Marine Studies (CESAM) & Department of Biology, University of Aveiro, 3810-193 Aveiro, Portugal
[b] Centre for Environmental and Marine Studies (CESAM) & Department of Chemistry, University of Aveiro, 3810-193 Aveiro, Portugal
[c] School for Resource and Environmental Studies, Dalhousie University, Halifax, Nova Scotia B3H 4R2, Canada
[d] Catalan Institute for Water Research (ICRA), H2O Building, Scientific and Technological Park of the University of Girona, Emili Grahit 101, 17003 Girona, Spain
[e] Water and Soil Quality Research Group, Department of Environmental Chemistry, Institute of Environmental Assessment and Water Research (IDAEA-CSIC), Jordi Girona 18-26, 08034 Barcelona, Spain

HIGHLIGHTS

- Plastic pollution threatens environmental sustainability.
- COVID-19 pandemic precautionary measures are reversing some plastic waste directives.
- Plastic production should be decoupled from fossil-fuel resources.
- Citizen-science approaches to reduce plastic pollution needs to be prioritised.
- Sustainable development calls for direct links between policy, industry and research.

GRAPHICAL ABSTRACT

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ABSTRACT

Plastics have been on top of the political agenda in Europe and across the world to reduce plastic leakage and pollution. However, the COVID-19 pandemic has severely disrupted plastic reduction policies at the regional and national levels and induced significant changes in plastic waste management with potential for negative impacts in the environment and human health. This paper provides an overview of plastic policies and discusses the readjustments of these policies during the COVID-19 pandemic along with their potential environmental implications.

The sudden increase in plastic waste and composition due to the COVID-19 pandemic underlines the crucial need to reinforce plastic reduction policies (and to implement them into action without delays), to scale up in innovation for sustainable and green plastics solutions, and to develop dynamic and responsive waste management systems immediately. Policy recommendations and future research directions are discussed.

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* Corresponding author.
E-mail address: ana.luisa.silva@ua.pt (A.L. Patrício Silva).

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1. Introduction

Plastics have a pivotal status in our modern society. The enhanced physicochemical properties (e.g., availability, flexibility, lightweight) and economic viability of plastics quickly conquered several industrial sectors, such as packaging, healthcare, fisheries and agriculture (Geyer et al., 2017). While the benefits of plastics are far-reaching, massive production and waste mismanagement have raised environmental concerns. In 2018, plastic production reached 359 million metric tons (Mt) (PlasticsEurope, 2019) while plastic waste generation reached 6.9 Mt (~3.2 Mt for short-life products); from which approximately 22% was incinerated, 25% recycled, and 42% inefficiently treated (i.e., either littered or inadequately disposed of in dumps or open landfills) (Hahladakis et al., 2018; OCDE Statistics, n.d.). Without improvements to the system, an estimated 12 billion Mt of plastic litter will end up in landfills and in the natural environment by 2050 (Geyer et al., 2017), along with greenhouse gas (GHG) emissions from the entire plastic lifecycle contributing to 15% of the total global carbon budget (Zheng and Suh, 2019). Thus, plastic mismanagement threatens the ability of the global community to meet carbon emissions targets and to combat climate change (United Nations Sustainable Development Goals 7 and 13; UN, 2013).

Plastics littered in the environments slowly degrade due to the action of abiotic factors (such as temperature, ultraviolet radiation, physical/mechanical processes) into plastic fragments of smaller size (e.g., microplastics, <5 mm and nanoplastics, <1 μm in size) (Frias and Nash, 2019). Low biodegradation, allied to the indiscriminate use and inappropriate disposal or mismanagement, has led to the accumulation of plastic debris in terrestrial and aquatic compartments worldwide, afecting natural biota, agriculture, fisheries, and tourism; and threatening human health and safety (Jambeck et al., 2015).

The accumulation of plastic waste in urban areas, particularly of sewage systems, can increase risk of floods (Adam et al., 2020; van Emmerik et al., 2018), constituting breeding grounds for vectors of zoonotic diseases (e.g., mosquito *Aedes* spp. as a vector of dengue and Zika) (Krystosik et al., 2019). In agroecosystems, the intense application and mismanagement of plastic mulching film (e.g., in Xinjiang province, China, plastic film residues can reach 381 kg ha^{-1}) have been related to soil degradation and poor crop development (Changrong et al., 2014). Carried out by wind, streams, rivers and currents, or through wastewater treatment plants, plastics debris can also be found in aquatic ecosystems, even in the most remote areas on Earth (e.g., lakes in isolated islands, Antarctica and deep-sea) (as reviewed by Ajith et al., 2020). Over 7 trillion microplastic pieces enter the North Pacific Ocean through San Francisco Bay every year (the 5 Gyres, 2019), and an estimated annual contribution of 1.2–2.4 million Mt of plastic waste enter marine systems via rivers (Lebreton et al., 2017). Once in natural environments, plastic debris can be voluntarily or involuntarily ingested. Plastic debris has been found in the gut of hundreds (or even thousands) of several species (see Litterbase, 2020), causing physical abrasions, and/or chemical toxicity due to the release of incorporated additives, adsorbed contaminants and pathogens (as reviewed by de Sá et al., 2018 and Karbalaei et al., 2018).

To decrease the environmental footprint of plastics, and plastic leakage to the environment, several international directives, national and local/regional initiatives, have been developed. Initiatives include fees, environmental taxes or outright legislative bans on certain single-use-plastics (SUPs) (e.g., plastic bag bans, and bans on microbeads) (Schnurr et al., 2018; Xanthos and Walker, 2017). However, the recent COVID-19 pandemic (a severe acute respiratory syndrome caused by a novel coronavirus - SARS-CoV-2) progressed rapidly (Worldmeter, 2019); and the preventive measures implemented to control and mitigate its high transmissibility involved a sudden surge in demand for, and consumption of, plastic products by the general public, healthcare workers and service workers. With human health being prioritised over environmental health, plastic reduction policies and plastic waste management strategies have recently been reversed or temporarily postponed (Prata et al., 2020). This paper starts by providing a thoughtful overview of plastic directives and the evolution of government policies on plastics use, production, and waste management during the pandemic. It follows with an in-depth discussion on their potential short-term and long-term environmental impacts. Finally, policy recommendations and future research directions are suggested.

2. Plastic waste directives

Due to the social, environmental and economic threats imposed by plastic pollution, numerous international agreements have been established. Among them are the Basel Convention and its amendment in 2019 (regulating transboundary moments of plastic waste), United Nations Convention on the Law of the Sea [UNCLOS] (controlling plastic pollution of the marine environment), International Convention for the Prevention of Pollution from Ships [MARPOL 73/78] (banning ships from dumping plastic at sea), Joint Group of Experts on the Scientific Aspects of Marine Environmental Protection [GESAMP], and United Nations Global Partnership on Marine Litter [GPLM] (both addressing inland sources, fate and effects of plastics and microplastics in the marine environment).

However, regional and national actions have been the primary approach to decrease sources of plastic pollution (*in situ*) by changing public behaviour and consumption patterns (Xanthos and Walker, 2017). SUPs represent more than 40% of the total production of plastics, with plastic bags and packaging as the most problematic types of waste as they are extremely difficult to recycle (~12% recycled) (CIEL, 2019). During their short lifecycle, SUPs contribute to widespread environmental pollution and a massive carbon footprint, so have been targeted by several national plastic reduction policies (CIEL, 2019). Starting initially with legislative tools to reduce plastic bags, actions now address more complex plastic items (e.g., packaging) (Schnurr et al., 2018). In 2018, the European Union [EU] released the first strategy for plastics in a circular economy aiming at banning 10 SUP products and fishing gear (constituting 70% of marine litter) by 2021 (European Commission, 2018; UNEP, 2018). As of July 2018, 127 countries were already implementing legislative measures targeting SUP products (e.g., packaging, including plastic bags), materials (e.g., polystyrene) or production levels (Nielsen et al., 2019; Schnurr et al., 2018; Xanthos and Walker, 2017; UNEP, 2018) (Fig. 1). From these, 91 have some type of ban or restriction on the manufacture or production, importation, and retail distribution of SUP (Fig. 1, countries coloured in green). Other measures include special environmental taxes, waste disposal fees or charges, and extended producer responsibility measures (e.g., deposit-refund, take-back schemes) (Diggle and Walker, 2020; Xanthos and Walker, 2017). Along with SUPs and fishing gear, microbeads have also been banned in several countries, such as Canada, France, Italy, Republic of Korea, New Zealand, Sweden, the United Kingdom, and the United States [U.S.] (Schnurr et al., 2018; Xanthos and Walker, 2017).

Non-legislative interventions have also been applied at citizen-level, NGOs and private sectors (Schnurr et al., 2018), which often translated into governmental actions. For example, the increase in zero-waste grocery stores highlights business opportunities reflecting consumer trends towards SUP reductions (Independent, 2018). The reuse and recycling of plastics, particularly SUPs, remains very low compared with other materials such as glass, paper, and metal (Ellen MacArthur Foundation, 2017; Geyer et al., 2017). Most end up in landfills, contributing to adverse environmental and health effects (e.g., decrease in land resources and release of GHGs) (Heidari et al., 2019). Improving plastic waste management (i.e., increasing recycling rates) is arguably less controversial than regulating its consumption or production, as recycling has broader support. Recycling is now being prioritised in several legislative landscapes as it provides opportunities to reduce oil usage, carbon dioxide emissions and quantities of waste requiring disposal. For

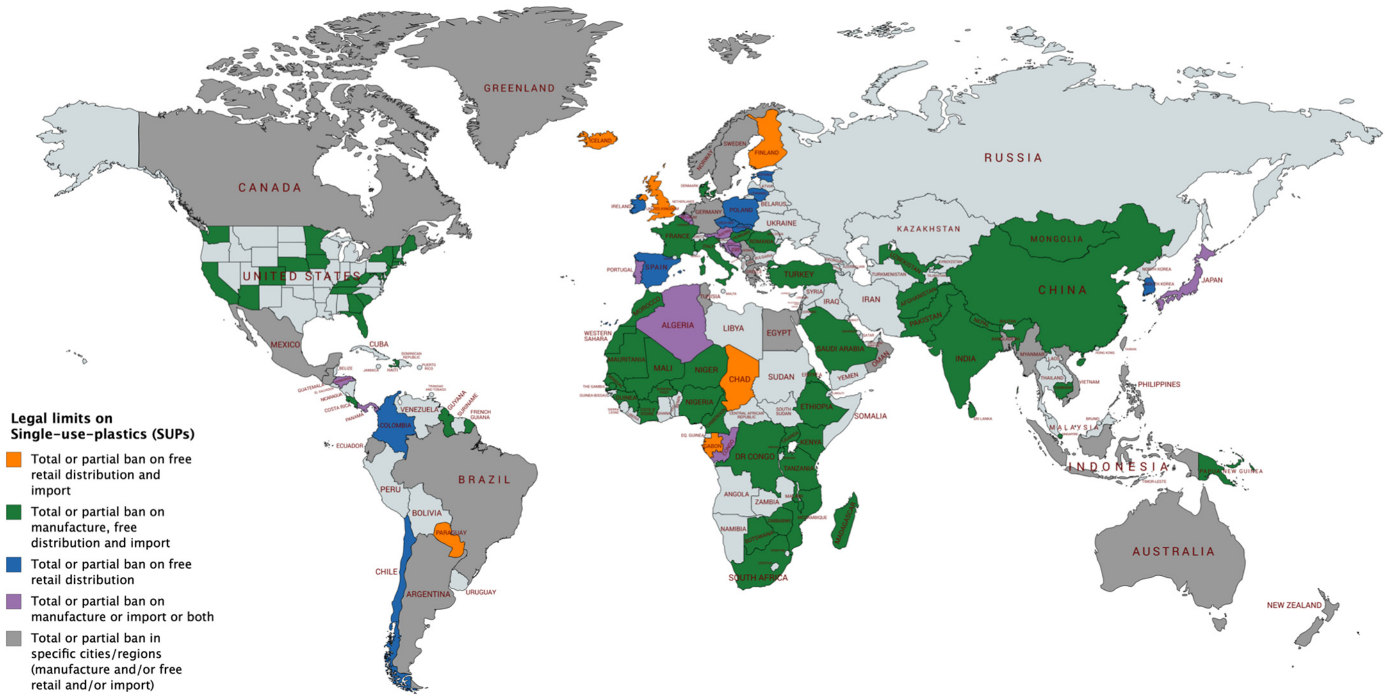

Fig. 1. Legal limits on single-use-plastics (SUPs) per country or state-wide in the case of the United States. Some islands and countries may not be discerned in the figure due to the map scale. Information based on UNEP (2018); NCEL (2019). Created with mapchart.net ©.

instance, the EU plastic strategy towards a circular economy is improving plastic waste management streams to prioritise recycling, including SUPs (European Commission, 2018). European Council, European Parliament and European Commission have even reached a preliminary political agreement that sets a target for recycling at 65% by 2025, to be increased to 70% by 2030, and a specific goal for plastic packaging recycling at 50% by 2025, to be increased to 55% by 2030 (European Commission, 2018; European Parliament and the Council, 2015). The increment of plastic recyclability is still a challenge, as it requires improvement of waste collection and plastic sorting approaches, along with the improvement of recycling streams (which are highly dependent on available infrastructures and economic resources) (Nielsen et al., 2020).

3. Plastic policies under the COVID-19 pandemic and potential environmental consequences

Despite the recent progress made in plastic sustainability and waste management, there have been widespread drawbacks in the use and management of plastics in the fight against the COVID-19 pandemic. Governments worldwide have implemented several precautionary measures to control/mitigate the high transmission of SARs-CoV-2, which included partial or total lockdown of cities/regions/municipalities, reduced economic activities and businesses to essential supplies, reduced mobility of goods and passengers, restrictions on social contact, mandatory quarantine for COVID-19 patients with minor symptoms, the creation of provisory treatment facilities for patients with moderate to severe symptoms, limited access to hospitals and healthcare facilities by family/visitors, and the incentive in the use of plastic-based personal protective equipment [PPE] (e.g., masks and gloves) by the general public (Tobías, 2020; Xiao and Torok, 2020).

COVID-19 preventive measures resulted in a high impact in the plastic industry and waste management. The shift on consumers' behaviour mostly driven by hygiene concerns, and the need to restock shelves quickly lead to a significant increase in the demand for food packaging (Jribi et al., 2020). In addition, concerns over cross-contamination caused by reusable containers and bags have been raised by the plastic industry in the past (e.g., Schnurr et al., 2018), which led to withdrawals or postponements of SUP bans and fees, supported by plastic industry lobbyists (Fig. 2). For example, some governments have delayed SUP bans amid COVID-19 concerns (e.g., the province of Newfoundland and Labrador in Canada, states of New York, Delaware, Maine, Oregon, Connecticut, Oregon, Hawaii, in the U.S., the United Kingdom and Portugal), while others reintroduced SUPs and even banned the use of reusable alternatives (e.g., the states of Massachusetts and New Hampshire in the U.S.). Alongside, the deposit return scheme of soft plastics has also been postponed. As an example, Scotland's deposit return scheme was delayed to July 2020 (BBC, 2020). The increased use and consumption of SUPs during the COVID-19 pandemic have resulted in an abnormally increased demand from plastic suppliers (e.g., China and U.S. [Bown, 2019]). In addition, the price of petroleum has fallen dramatically due to the decrease in water, land and air transport, which is favouring the manufacturing of virgin plastics (over recycled plastics) by the plastic industry.

SUP accounted for 46% of all plastic waste globally in 2018 (UNEP, 2020), with China as the primary contributor (i.e., the largest worldwide producer and generator of SUP waste), followed by U.S. (as the largest generator of SUP waste per-capita), Japan and the EU (Bown, 2019; UNEP, 2020). The demand for SUPs will substantially increase not only during the COVID-19 pandemic but mostly after confinement.

The premature withdrawal of SUP reduction policies (mainly plastic bags) was contested as many consumers have already adjusted to using non-plastic alternatives motivated by these policies (Xanthos and Walker, 2017) and the contribution of reusable grocery bags in the transmission of SARS-CoV-2 remained questionable, especially when coupled with proper hygiene practices, such as regular hand washing and frequent laundering of reusable bags.

The mandatory use of PPE by the public (once mandatory only for frontline healthcare workers) during, but mostly after, confinement also increased significantly. Over 50 countries required the use of masks in public places and transports, including Venezuela, Portugal, Spain, Czech Republic, Bosnia and Herzegovina, Cuba, Ecuador, Austria, Morocco, Argentina, Luxembourg, and El Salvador (Fig. 3).

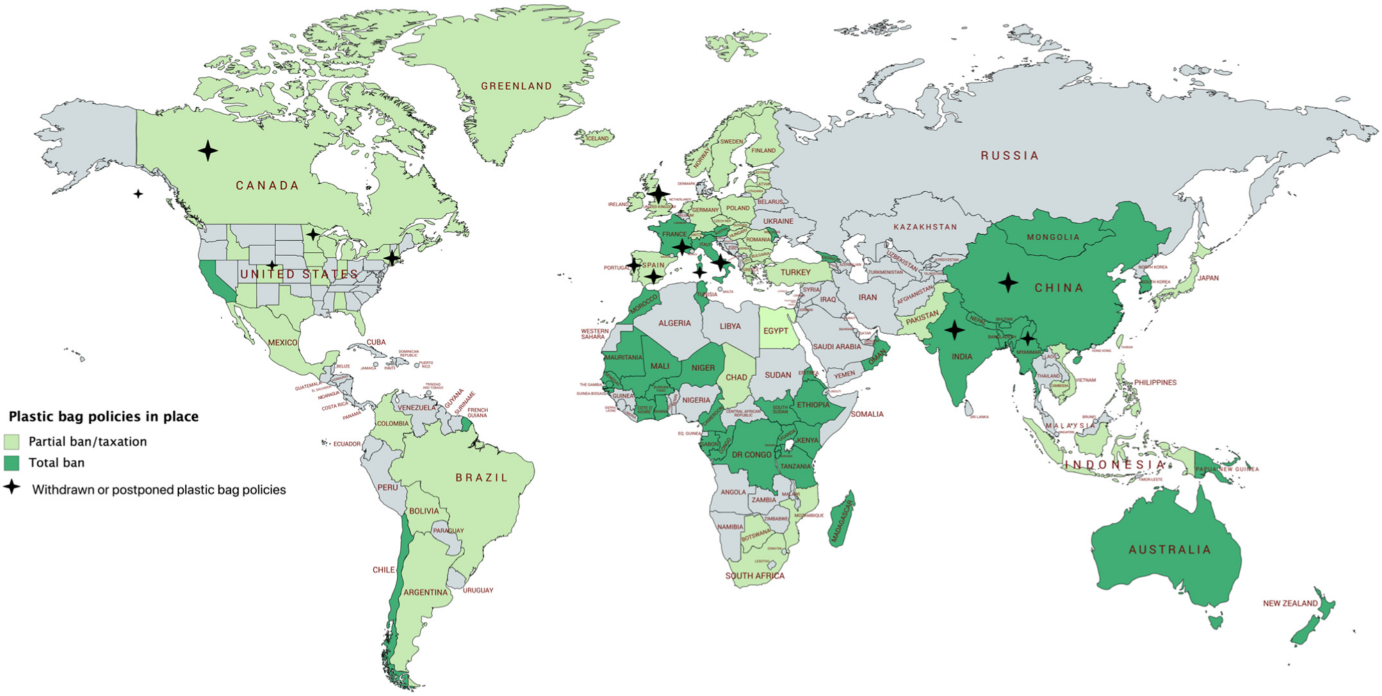

Fig. 2. Government initiatives on plastic bag reduction policies. Black four-pointed stars represent countries or states (in case of the United States, U.S.) that have withdrawn or postponed plastic bag initiatives. Some islands and countries may not be discerned in the figure due to the map scale. Information based on Nielsen et al. (2019); Schnurr et al. (2018); Xanthos and Walker (2017); UNEP (2018); NCEL (2019). Created with mapchart.net ©.

Similarly, to SUP, increased PPE demand led to increased production. As an example, China increased face mask production by 450% in a month (i.e., from 20 to 110 million, as of February 2020), and demand for N95 respirators has grown from about 200,000 to 1.6 M (Bown, 2019).

The use of masks by ordinary citizens quickly became controversial due to the lack of correct handling and disposal, and the shortage of this material in healthcare facilities (World Health Organization, 2020). Surgical masks should not be worn longer than a few hours (e.g., 3 h), and should be adequately discarded to avoid cross-contamination (i.e., in sealed plastic bags). Besides being a public health concern, incorrect disposal of PPE quickly spread in several public places and natural environments (Prata et al., 2020). For instance, tens of disposable masks were observed in a 100 m stretch in Soko's islands beach, Hong Kong, during an environmental survey carried out by the NGO Oceans Asia (NGO Oceans Asia, 2020). Masks are made of nonwoven materials (e.g., spunbond and meltblown spunbond) often incorporating polypropylene and polyethylene and will likely degrade into smaller microplastic pieces (Prata et al., 2020). In the Magdalena River, Columbia, the degradation of nonwoven synthetic textiles was the predominant origin of microplastic microfibres found in both water and sediment samples (Silva and Nanny, 2020).

Aside from the increased use and disposal of PPE (masks and gloves) and plastic bags, other SUPs are being used extensively by some business sectors while restarting their activity in a post-pandemic scenario. Some examples include the use of: i) cleaning microfibre wipes for cleaning, disposable feet protection, head caps and cuffs to enter/work in healthcare clinics and beauty salons; and ii) protective plastic films/protectors in chairs, payment machines, balcony/desk, to avoid potential contamination by air droplets, which is replaced after business hours.

The substantial increase on the use/consumption of SUPs and PPE, along with the increment on medical waste inherent to the pandemic, is likely leading to an overload increase in waste generation, disrupting viable options of proper waste management (Prata et al., 2020). Due to the persistence and high contagiousness of SARS-CoV-2, many countries classified all hospital and household waste as infectious (e.g., European Commission, 2020), which should be incinerated under high temperatures (allowing sterilisation), followed by landfilling of residual ash (Windfield and Brooks, 2015). While some countries or municipalities are capable of managing such waste properly, others (with fewer resources) are being forced to apply inappropriate management strategies such as direct landfills or open burnings. In the global south, most urban areas are already lacking sufficient options or resources for the increasing general amount of waste generated (Hoornweg and Bhada-Tata, 2012), and the significant input of SUPs and PPE into their economy during the pandemic scenario is creating a higher logistical challenge in the waste management service provision. For instance, the sharing of plastic recycling in India was around 60% (Alpizar et al., 2020). However, uncontrolled landfilling and local burning strategies on plastic waste increased substantially in some Indian municipalities during COVID-19 pandemic, as an attempt to avoid virus contagion (Corburn et al., 2020). On the other hand, countries with larger economies were able to overcome the adversities of COVID-19 on plastic waste management. As an example, Wuhan, China, deployed mobile incineration facilities to treat the four-fold increment on infectious waste generated during the COVID-19 outbreak (Saadat et al., 2020).

While in a short-term scenario the COVID-19 pandemic is increasing the overall human health and safety (e.g., improved outdoor air quality, decreased in smokers and consequently in litter from cigarette buts, decreased household food waste and GHG emissions); the drastic increase use and mismanagement of SUPs and PPE will likely entail long-term adverse effects to the environment (Prata et al., 2020). As examples, landfills and incineration were prioritised during the COVID-19 pandemic, resulting in burying or burning considerable amounts of plastic items. Such plastic waste management strategy results in increased environmental footprint as the energy of plastic materials are lost and contribute to significant releases of GHGs and hazardous compounds to the environment (Heidari et al., 2019). Likewise, most PPE (masks and gloves) and SUPs are lightweight and if discarded in open dumps can be easily carried by wind and surface currents, quickly spreading to

Fig. 3. Mandatory (or highly recommended) use of masks per country or state-wide in the case of U.S. Some islands and countries may not be discerned in the figure due to the map scale. Created with mapchart.net ©. More info Aljazeera News (2020); DN (2020a, 2020b); Andrew and Froio (2020); Sheridan (2020). Created with mapchart.net ©.

natural environments nearby, threatening (e.g., by entanglement) aquatic and terrestrial biota. According to the WWF report, over 10 million masks can be introduced in the environment monthly considering an incorrect disposal of only 1% (WWF, 2020). Considering that each mask weighs approximately 3–4 g, it would result in 30–40,000 kg of masks in natural environments (WWF, 2020; Fadare and Okoffo, 2020). Once in the environment, such plastic items will degrade, contributing to the already substantial levels of microplastics worldwide. Thus, the COVID-19 pandemic is imposing a significant challenge not only to environmental and human health but also to global economic and societal systems and plastic waste management.

4. Policy recommendations

The COVID-19 pandemic emphasised the dependence on disposable plastics (e.g., increased demand for SUPs and PPE) and fragility of the system regarding waste management and plastic reducing policies, being relevant even in the post-pandemic world due to their long-term repercussions. A question arises regarding the possibility of reducing plastic use and consumption without compromising our health and the environment. Pandemics are recurrent throughout human history; thus, the search for sustainable solutions must be prioritised, now more than ever. This involves scaling up on responsibility (from stakeholders and governments) and innovation (from academia and research industry) to rethink the design and management system of plastics by moving forward and faster to a model that considers plastics entire life cycle (i.e., from design/production to end-of-life options – instead of independently optimising each stage) (Prata et al., 2019, 2020). As the major environmental problems allied with the plastic pollution during COVID-19 pandemic resulted from: i) high demand on SUPs; ii) high demand of PPE; iii) increased medical waste, and iv) prioritisation of incineration and landfill; the following recommendations are proposed:

4.1. Redesign plastics and decouple them from fuel-based resources

The replacement of the plastics value chain from fuel-based raw materials and energy is already being prioritised as part of international agreements to entail a green and circular economy. Such transition and the decoupling from fossil fuel-based resources needs to be prioritised in a shorter-term, by developing a more supportive legislative landscape and a clear direction. Bio-based plastics are, indeed, emerging as a sustainable solution at an early stage, but their market share is less than 2% (i.e., ~7.4 of 348 million Mt in 2017) (PlasticsEurope, 2019; Nova-Institute, 2019), mostly due to the low-cost of fossil-based plastics (Hatti-Kaul et al., 2020), the intense requirement for land use and related financial investment, and the undeveloped recycling and/or disposal routes (Chanprateep, 2010). The use of biorefinery as a biotechnological tool to obtain raw materials from biomass by-products and waste flows (both organic and gaseous), seems to be a promising alternative to boost bio-based plastics; as it overcomes the need of land and has the potential to increase production patterns (thus decreasing the price of such solutions) (Hatti-Kaul et al., 2020). Enormous efforts must, however, be driven to the screening and development of microbial strains with enhanced hydrolytic capacities that would allow direct conversion of biomass (e.g., agricultural, food and forestry residues, algal biomass), and the extraction of value-added products (e.g., bioactive compounds, proteins, pectin) for the synthesis (polymerisation) process (Hatti-Kaul et al., 2020). With such approach, high-performance bio-based polymers with desirable material features allied with increased potential for sustainable end-life options will hopefully soon emerge (as reviewed by Loannidou et al., 2020; Zhu et al., 2016).

The development of bio-based solutions with identical physical properties to fuel-based counterparts (including low degradability/high durability, e.g., polypropylene) would be of interest for the production of, for instance, face shields, respirators, ventilators, space/counter dividers, syringes, and boots during pandemic scenarios, as it would allow their reuse or their processing (and thus increasing energy recovery) in the existing infrastructure after proper decontamination. On the other hand, the development of bio-based and biodegradable/compostable solutions for food packaging, masks, gloves and other disposable plastics, would decrease their environmental pressure when considering landfill or waste-to-energy options. Nevertheless, dynamic cradle-to-grave life cycle assessment of such bio-based alternatives is urgently required, along with the assessment of potential incompatibilities (i.e., in the recovery/recycling process). Likewise, the environmental footprint of plastic production and the environmental footprint of plastic waste should be used as a medium to evaluate new plastic solutions sustainability compared to the alternatives (e.g., paper bags) (Klemeš et al., 2020).

The design, feasibility and end-life of bio-based products at laboratory scale should be validated at pilot-scale before real-world applications, which reinforce the importance of the synergies between academia (where most applied research is carried out) and stakeholders/plastic industry. Likewise, their environmental safety must be adequately addressed and labelled, which will require an update on the current tests, such as the American Society of Testing and Materials (ASTM) and the International Standards Organisations (ISO), as they mostly rely on respirometric methods and unrealistic test conditions (Lambert and Wagner, 2017). The transition of fossil-based to bio-based plastics should also be built on an improved circular and integrated system (from cradle-to-cradle), also relying on close monitoring as well as on legal requirements, extended producer responsibility, fees incentivising better design and non-hazardous material use, and public awareness. In addition, the plastic industry should apply profits from SUPs, or be financially supported by governments, towards such sustainable options. COVID-19 pandemic might have induced cumulative changes in the generalised economic structures, but this should not shift our trajectory towards sustainable plastics solutions.

4.2. Reduce plastic waste by reducing SUPs and PPE

Although SARS-CoV-2 virus viability on different materials/surfaces (metal, cardboard, plastics, textiles) has been proved (Chin et al., 2020), it remains unclear if there is indeed a risk of infection. Thus, these materials should be substituted by low-carbon reusable alternatives whenever possible. For instance, plastic or reusable fabric bags should be preferred when packaging groceries (including over paper bags), even when no fees or bans are in place. Alternatives include 100% reusable, recyclable or compostable plastic packaging already available in the market. Other examples include the use of reusable PPE by the general public, instead of disposal after a single-use. In the case of SARS-CoV-2 or other highly transmissible pathogens, use of proper hygiene and sterilisation could mitigate concerns over reusable packaging and PPE (Chin et al., 2020).

Similarly, fees, taxes and bans on fuel-based SUPs should remain incentivised. These changes should be supported by the public and scientific community, increasing the pressure on the plastic industry and governments. For instance, the introduction of a small 15 Euro cents per bag fee in 2002 led to a reduction of 90% in the use of SUP bags in Ireland while having high public support (Xanthos and Walker, 2017). Therefore, public awareness on the consequences of plastic pollution must increase dramatically (through social media, governments, stakeholders) and mis-behavioural should be penalised (e.g., higher fees on waste generation) (Schnurr et al., 2018). Similarly, reusable PPE solutions should be used during pandemics as long as they do not compromise public health, requiring pacifying the public regarding their safety. The 10Rs of sustainability policy, especially during the pandemic, should be financially incentivised (i.e., refuse-reject, rethink, reduce, reuse, repair, refurbish, remanufacture, repurpose, recycle, recover) (Potting et al., 2017). Greater synergy between academia-stakeholders-citizens is crucial to produce the intended results of 10R, maximising the benefits (e.g., via "citizen-science"), while redesigning to reduce the use, consumption, pollution and (in certainty way) costs of plastics. Raising public awareness on the adverse effects of plastic pollution in the environment is crucial to continuously contribute to the reduction of plastic leakage, as well as exert pressure on governments and industries to follow suit. Recycling, composting, and incineration (waste-to-energy, as a last resort), should be assessed as priority end-of-life solutions for plastics. However, this requires international resource sharing, especially benefiting developing countries.

4.3. Optimise plastic waste management

During COVID-19 pandemic, medical waste (along with generalised SUP and PPE) increased significantly at worldwide level. This scenario calls for a stronger regulation (in terms of tracking, treatment and disposal of medical waste) at national, but mostly international levels to converge efforts and strategies, and increase efficiency on medical waste management. Pre-sorting and disinfection of medical waste should be incentivised and optimised to improve their potential recyclability.

Governments must also improve waste management (with particular emphasis to developing countries), aiming at achieving maximum collection and recycling, and to avoid plastic mismanagement and littering leading to contamination (and plastic leakage). In the EU, both "Waste Framework Directive" and the "Packaging and Packaging Waste Directive" were revised by the European Parliament, setting new goals for recycling and prioritising the importance of bio-based feedstocks to contribute for a sustainable production of plastics and more efficient waste management (EC, 2018). Such strategies/approaches must be put in place in a short-term, and must include, for instance, i) the increment in the number of disposal facilities, ii) enhancement of infrastructures (i.e., recycling, composting and, as last resorts, landfilling and waste-to-energy), iii) increasing coordination between stakeholders, authorities and local workers; and iv) empowering producers, retailers and municipalities. When recycling is not possible, plastic waste should be used as feedstock or in waste-to-energy, which are easier to implement in the short-term (Prata et al., 2019). Indeed, some plastic wastes cannot be recycled (e.g., composites, highly degraded materials) and should have an alternative end-life besides landfilling (Braungart et al., 2007). The use of recycled plastics is currently also hindered by the low costs of virgin materials, which could be overcome through the implementation of taxes or minimum requirements for the use of recycled materials (Singh and Ruj, 2015). In the use of disposable PPE by the public, end-of-life strategies need to be rethanked regarding the proper disposal in sealed impermeable bags or neutralised through sterilising techniques. Since plastic pollution is not restrained by political boundaries and has a global impact, international cooperation is essential, especially in the sharing of knowledge, technology, and funding. Finally, science should be prioritised and cultivated, as our future relies on technological and scientific knowledge to overcome adversities. Thus, synergies between stakeholders, academia, citizens, and the government should be straightened.

5. Concluding and future directions

Humanities dependence on plastic as a material has been put to test with the current COVID-19 pandemic, emphasising the need for stronger policies to ensure future sustainable use of plastics, while extracting the most benefits (e.g., economic, safety and hygiene), and minimising negative consequences (e.g., plastic waste mismanagement). To achieve this, it is crucial to identify the major needs, to establish priorities, to implement policies with "real" results in a short run. Several plastic directives have been adopted and, now more than ever, should be implemented. During COVID-19, the use of SUPs and PPE increased significantly; thus, the need of rethinking and redesigning plastics (i.e., development of eco-friendly and bio-based solutions at an affordable price), along with the improvement of recycling streams to ensure proper end-of-life for those products (during pandemic scenarios), should be at the highest priority. Reusable alternatives (such as for PPE) should be produced and financially incentivised (here, at the industrial sector level). Increased public awareness, and customers preferences for sustainable solutions, will contribute to the implementation of good practices, as well as exert pressure on governments and industries to follow suit.

With public health being the utmost priority, the implications of COVID-19 in the environment remain mostly undervalued. Although the number of studies addressing the environmental impact of COVID-19 pandemic (e.g., in the air quality, carbon footprint) is increasing in a daily basis, it remains unclear the extent of the "physical" impact of plastic pollution during COVID-19 and what will happen in the long-term. The amount of waste generated due to COVID-19 indeed threatens the existing waste management streams, meaning that plastic leakage/pollution may impose severe risks to both environmental and human health. Thus, it is imperative to increase monitoring (aquatic, terrestrial and aerial surveys) of plastic waste under post-COVID-19, around the world. Citizen science (i.e., NGOs) must be incentivised as it would greatly contribute to this cause. Furthermore, studies addressing the fate, behaviour, degradability and effects of PPE (their additives, potential for pathogens transfer, and adsorbent capacity of chemical pollutants) should be prioritised.

CrediT authorship contribution statement

Ana L. Patrício Silva: Conceptualization, Project administration, Funding acquisition, Visualization, Writing - original draft, Writing - review & editing.**Joana C. Prata:**Visualization, Writing - original draft, Writing - review & editing.**Tony R. Walker:**Visualization, Writing - original draft, Writing - review & editing.**Diana Campos:**Visualization, Writing - original draft, Writing - review & editing.**Armando C. Duarte:** Conceptualization, Supervision, Project administration, Funding acquisition, Writing - review & editing.**Amadeu M.V.M. Soares:**Writing - review & editing.**Damià Barcelò:**Conceptualization, Supervision, Writing - review & editing.**Teresa Rocha-Santos:**Conceptualization, Supervision, Project administration, Funding acquisition, Writing - review & editing.

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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