Environmental Science and Pollution Research (2021) 28:46067–46078
https://doi.org/10.1007/s11356-021-15425-w

SHORT RESEARCH AND DISCUSSION ARTICLE

Plastic and its consequences during the COVID-19 pandemic

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Received: 18 January 2021 / Accepted: 8 July 2021 / Published online: 19 July 2021
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Abstract

During the pandemic outbreak of COVID-19, the important role of plastic becomes evident since vital equipment such as respirators have plastic parts, as well as personal protective equipment (PPE), which avoids the transmission of the SARS-CoV-2 virus, is made of plastic. So, plastic during a pandemic is considered a life savior in the struggle against the virus. However, the same material that is a protector becomes a polluter when inadequately disposed of in the environment, generating or worsening socio-environmental problems, such as pollution of water bodies by plastic. This work proposes a reflection about the role and the importance of plastic in our society, bringing an overview of its main applications and consequences during the COVID-19 pandemic, correlating its use with aspects related to environmental problems and public health. Some questions revolving around the concerns caused by plastic pollution are posed, and some possible solutions to the problems are outlined.

Keywords COVID-19 · Plastic · Personal protective equipment · Virus spread · Recycling · Public health · Environmental problems

Introduction

The world is experiencing a major global crisis. According to Pope Francisco (Francisco 2020), going into crisis means being "sifted through." It is a time when both our parameters and our ways of thinking are shaken and our priorities and lifestyles are called into question. We cross a threshold, either by decision of our own or by necessity, because there are crises, like the one we are going through, that we cannot avoid.

Thinking about lifestyle, there is no way to separate the current way of life and plastic. It is ubiquitous. During the COVID-19 pandemic, plastic has gained media attention and its role is being proven. Due to the large application of plastic as raw materials in the production of personal protective equipment (PPEs), it emerged as a life savior for protecting the health and safety of the frontline health workers and the common citizens in the time of the pandemic (Parashar and Hait 2021). So, plastic has been a protector in the ongoing COVID-19 pandemic.

The COVID-19 pandemic reveals alarming records, not only of confirmed cases and deaths but also of the amount of plastic waste generated, such as hospital waste, post-used PPEs, confirmatory COVID-19 testing and vaccination residues, and packaging in general (some data will be provided in sequence). However, the increase in the amount of residues generated demonstrates the fragility of the management systems of residues worldwide, being aggravated by the lack of public policies and awareness of large part of the population.

The consequences of the increased use of plastic in different applications during the COVID-19 pandemic are aggravating environmental problems, turning plastic into a legitimate villain, even though being a life savior. Undoubtedly, for those who were hospitalized or had a family member hospitalized could more strongly experience the life savior role of plastic during the COVID-19 pandemic due to the application of plastic in hospital devices which are fundamental for vital and organic support. In fact, plastic is our great partner and we collaborate to turn it into a villain, through the inadequate final disposal of post-used plastic, regardless of its application.

Given the importance of plastic during the ongoing COVID-19 pandemic, this work aims to discuss its main applications and consequences, as well as some possible solutions, based on recent literature.

Responsible Editor: Lotfi Aleya

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Transmission forms of COVID-19 and stability time of the SARS-CoV-2 active virus

Before discussing the application of plastic during the COVID-19 pandemic, it is essential to understand the three main forms of the COVID-19 transmission, namely, from person-to-person (no physical contact is necessary), via airborne transmission (solid components of evaporated respiratory may remain in the air), or via fomite (contaminated objects). All of them are the result of droplets (respiratory tract fluid containing active virus) released during a sneeze, a cough, a speak, or even through breathing from an infected person who contaminates a susceptible individual. Figure 1 schematically shows the main ways of the COVID-19 transmission. This is essential to understand the role of plastic during the pandemic the world is facing.

Respiratory droplets containing the active virus can be of different sizes, and those droplets larger than 20 μm rapidly settle onto surfaces because of the gravity and do not travel distances higher than 1–2 m (Morawska 2006), contaminating any place where it comes to fall. When contaminated, plastic may infect susceptible people: SARS-CoV-2 virus (name of the coronavirus responsible for COVID-19), present in the droplets, may remain active between 4 and 7 days in plastic (Chin et al. 2020; van Doremalen et al. 2020). According to the Centers for Disease Control and Prevention (CDC) (2021), at homes, disinfection to reduce the transmission of COVID-19 is likely not needed unless someone at home is sick, or if a positive for COVID-19 person has been in the place within the last 24 h. However, in public places such as a supermarket, where the movement of people is commonly large, a certain packaging can be contaminated, so it is important to do the hygiene of items as soon as you arrive with the purchases at home to avoid the possibility of transmission via fomite. By touching a contaminated object and touching the eyes, mouth, or nose (before washing the hands), a healthy person can get infected (de Sousa 2020; Swelum et al. 2020). So, even knowing that person-to-person is the main transmission way, the transmission via fomite cannot be completely dismissive.

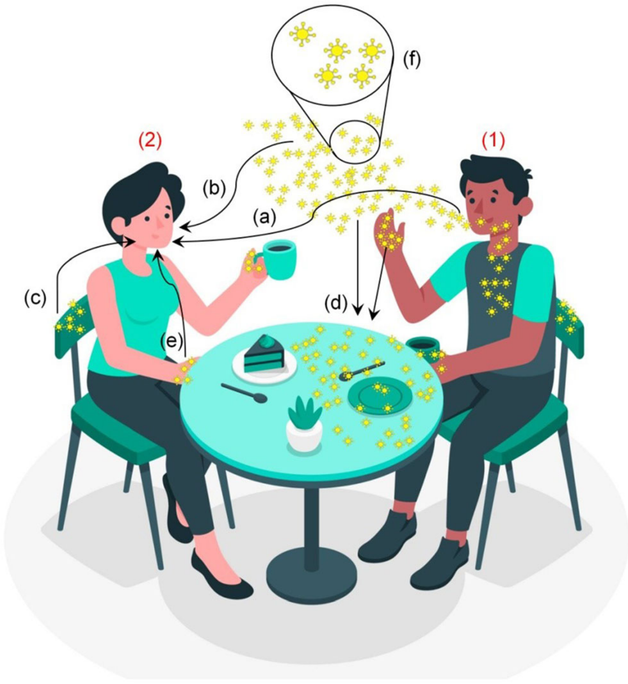

Fig. 1 Schema showing the main ways of the COVID-19 transmission, in which the person (1) is infected (even being asymptomatic), and person (2) is not yet infected (susceptible individual): **a** person-to-person and **b** via airborne or aerosol. **c** Via fomite, an indirect way of transmission. **d** Contaminated objects, such as the table, are the result of the droplets fall containing active virus present in the airborne/aerosol and/or by the contact of the infected person. **e** By touching a contaminated object and touching the eyes, mouth, or nose, a healthy person can get infected. **f** Magnification of the active virus, present in the droplets excreted from the mouth and nose when the infected person sneezes, coughs, speaks, and breathes (de Sousa 2020)

The stability of the virus depends on the type of the material (glass, plastic, etc.), due to the wettability degree of the droplet on a specific surface, the result of the bonding force between the droplet/surface interfaces. It is influenced by the characteristics of the droplets (viscosity, temperature, etc.), surface (especially roughness), and environment (room temperature, humidity, air speed, etc.). However, there is no consensus so far on which factor is predominant in the survival time of the virus, and many studies diverge from each other. Therefore, it is essential to maintain personal hygiene protocols and sanitize all packages, as they may be contaminated. There are some possible products to be used, with proven efficiency in virus inactivation (Chin et al. 2020).

The importance of plastic in the battle against the SARS-CoV-2 virus will be analyzed through the analysis of its main applications.

Application of plastic during the COVID-19 pandemic

In 2019, global plastics production reached 368 million tons (2020a), being 49% single-use items (Ogunola et al. 2018). Its production has demonstrated a massive increase, from 2 Mt in 1950 to around 380 Mt in 2015 (Geyer et al. 2017). The packaging sector accounts for about 40% of the consumption of all plastic material produced on the planet (2020b), and around 17% of the total consumption is composed of the medical sector, appliances, mechanical engineering, and furniture (2020b). Most packages are discarded shortly after use, making this sector, possibly, responsible for a significant portion of some negative environmental impacts, mainly the pollution of water bodies by plastic. Around 6300 Mt of plastic waste had been generated up to 2015, being recycled only about 9% of this amount (Geyer et al. 2017). Consequently, a recent estimate (Borrelle et al. 2020) concerns that the amount of plastic that reaches water bodies causing pollution in 2016 was equivalent to 19 to 23 Mt, which can reach up to 53 Mt per year by 2030.

Trying to avoid the overload of hospitals, preventive measures were adopted worldwide such as social distancing, isolation, travel restriction, and new hygiene protocols were introduced, especially for cleaning hands. Likewise, the massive use of face masks by the world's population was recommended by the World Health Organization (WHO) to slow down the transmission rate of COVID-19 in human beings.

According to the WHO (2020), PPEs include gloves, medical/surgical face masks, goggles, face shields, gowns, respirators (N95 or FFP2 or FFP3 standard or equivalent), and aprons being made, primarily, of single-use plastics. All these aforementioned PPEs are made of plastic. At the beginning of 2020, the WHO modeled an estimate for the PPEs required worldwide for the COVID-19 response monthly, only for health workers (2020): 89 million medical masks, 76 million gloves, and 1.6 million goggles. American officials have estimated that the country would need 3.5 billion masks to cope with a year-long pandemic (Bradsher and Swanson 2020).

The International Solid Waste Association estimated consumption of 250 to 300% more single-use plastic than used during pre-pandemic. Approximately 130 billion face masks and 65 billion gloves are used globally every month nowadays (Vasil 2020). In 2020, China produced 116 million masks a day, or about 12 times what was produced before the pandemic (Bradsher and Swanson 2020). The number of face masks used daily in the world is estimated to reach over 7 billion (Hantoko et al. 2021). During the COVID-19 pandemic, the packaging materials and others (which includes medical stuff) are projected to increase (44.8 and 13.2%, respectively) due to the demand for PPEs, food delivery services, and online groceries (Hantoko et al. 2021). Diverging slightly, Prata et al. (Prata et al. 2020) estimated that the demand for plastics is expected to increase by 40% in packaging and 17% in other applications, including medical uses. The global packaging market size is projected to grow from USD 909.2 billion in 2019 to USD 1,012.6 billion by 2021, with an annual growth rate of 5.5% (2020).

Based on all seem up to now, questions about the role of plastic as a protector or a polluter are arisen.

When correctly sanitized, the packaging protects its contents from contamination, especially in the case of food. It is also important to have in mind that packaging reduces waste as it protects food and increases its shelf life. Thus, plastic packaging acts as a kind of barrier, protecting the population from different types of contamination, not only COVID-19. The great advantage of plastic applied in packaging, thinking of pandemics, is that they are waterproof and, thus, can be washed and sanitized without contamination of the food. With this, the possibility of indirect contamination is reduced (Fig. 1).

Additionally, thinking about hospitals, the role and importance of plastic during the pandemic become even clearer. Most of the devices used in hospitals to save lives, especially dealing with COVID-19, are made totally or partially of plastic.

After 13 months into the COVID-19 pandemic, unfortunately, I had a family member hospitalized by COVID-19 and I was able to experience the use and the importance of plastic devices in the treatment of patients. From the first procedures in the hospital emergency in an attempt to save her life, it was perceived the use of devices such as thermometer and oximeter, catheter and tube for application of medication and saline solution, and packages of saline solutions; all made of plastic. Subsequently, in the hospital room, in addition to the use of the same health care items, others such as the mask for high flow of oxygen, tubes for the oxygen flow, syringes, not counting the packaging of all foods, single-use cups, and cutlery were used. Having had her health worsened and transferred to the intensive care unit (ICU), the need for other more complex equipment increased. On the last visit to say her goodbye in the ICU, it could be observed the high number of equipment and devices for vital and organic support, several modalities of monitoring of body functions essential for life such as respirator, heart and blood pressure monitors; flow meters, controllers, and sensors for saline solutions, medicines, and food; oximeter; thermometer; and others not less important such as tubes, suction and urinary probes, catheters, and diapers. She lost the battle to COVID-19, but throughout the hospitalization period, all the equipment and devices aforementioned and others were essential to her treatment and maintenance of her life, all of them made or having some plastic part.

Furthermore, no less important, the bodies of COVID-19 victims receive a different number of protection layers, varying according to each country's standards, before being placed in a sealed coffin. Generally, at least one waterproof bag (made of plastic) is used to prevent the leakage of liquids and secretions (Behera 2021). The number of victims worldwide by COVID-19 is alarming and grows every day. So, will such plastics become another environmental problem soon?

Other very important applications are as thickening agent in alcohol gel as well as vials and disposable syringes used in the vaccination of the population against the COVID-19.

The high demand has led to a shortage of PPEs and alcohol gel, as well as the raw materials for their manufacture, especially in the early pandemic, leading the population to seek other protective alternatives such as face masks made of cloth. These masks have some advantages such as being washable and cost-effective (Ardusso et al. 2021), in addition to being effective as a barrier for aerosol (Konda et al. 2020). The fabrics used can be synthetic or natural. The most employed synthetic fabrics are chiffon, spandex, cotton quilts, flannel synthetic silk, and their combinations, being the most employed polymers in the manufacture of these textiles the polyester, nylon, or polyether-polyurea copolymer (Konda et al. 2020).

Consequences of plastic during the COVID-19 pandemic

Currently, more than an outbreak, we are facing the magnification of the plastic pollution crisis. The environment is being damaged due to the increased use of plastic in different applications during the COVID-19 pandemic, inefficient management of residues, and lack of public policies and awareness of a large part of the population. According to Parashar and Hait (Parashar and Hait 2021), “the consumers’ irresponsible behavior, and attitude and poor awareness, and the stress on waste management infrastructure in terms of collection, operation, and financial constraints as the major drivers, leading to mismanagement, turn plastic into an evil polluter of the environment.” The main consequences of the use of plastic will be briefly discussed.

PPE waste produced both by hospitals and by the population is considered a contaminated residue, no matter the material used in the production (in the case of face mask) since it is hazardous in terms of being pathogen contaminated (de Sousa 2020). Post-used PPEs should be handled as infectious materials by healthcare professionals and citizens alike (Prata et al. 2020). While PPEs from medical sectors are sterilized, incinerated, or autoclaved, the ones produced by the population cause stress to the infrastructure and waste management systems of cities (Ammendolia et al. 2021).

The increase in the amount of waste generated due to the COVID-19 pandemic, such as post-used face masks and gloves, has been tremendous since the beginning of the pandemic. Only in Brazil, an estimate shows that more than 85 million face masks might be disposed of per day (Urban and Nakada 2021). Preventive measures such as the use of face masks were imposed on the population, but no clear instructions and disposing mechanisms were provided. Perhaps this was the establishment of the environmental challenge caused by such waste in the outbreak scenario.

Such waste needs to be properly disposed of. However, it is not uncommon to find them disposed of in inappropriate places (Cordova et al. 2021; De-la-Torre and Aragaw 2021; De-la-Torre et al. 2021; Fadare and Okoffo 2020; Kalina and Tilley 2020; Saliu et al. 2021; Selvaranjan et al. 2021). Cordova et al. (Cordova et al. 2021) reported a 5% increase in the abundance of debris and a 23–28% decrease in the weight of debris releases in March–April 2020 compared to March–April 2016 at two river outlets: the Cilincing and Marunda Rivers at Jakarta Bay, Indonesia. The results confirmed an unprecedented presence and variety of PPEs during the pandemic, representing 16% of the collected river debris. According to the authors, PPEs were not verified before the pandemic. The authors observed the different PPEs such as cotton mask, sponge mask, medical mask (surgical, N95), medical gloves, hazard suit material, face shield, and raincoat as a substitute for hazard suit. Plastics remain as the dominant riverine debris at 46% by abundance and 57% by weight.

The massive use of face masks by the population is an effective measure to slow down the transmission rate of COVID-19 (Fig. 1). However, the use of plastic in face masks and other PPEs, effective partners in the fight against the virus, can become a major problem when improperly disposed of in the environment. Such waste disposed of in inappropriate places ends up, in one way or another, destined for bodies of water (the residues are advected by wind, stormwater, drainage systems, and wastewater (Eriksen et al. 2013), reaching rivers, seas, and/or oceans) (Auta et al. 2017). Macro-, micro-, and nanoplastics are present in the waters, being microplastics (MPs) (< 5 mm in size) the major component of plastic pollution. MPs can be divided into primary and secondary origins, being the primary ones produced by industry (such as microbeads present in cosmetics) and the secondary origin the result of the degradation of macroplastics.

Literature shows that disposable face masks are sources of microplastics in the environment (Aragaw 2020; Fadare and Okoffo 2020; Saliu et al. 2021) and, additionally, they act as pollutant carriers. Anastopoulos and Pashalidis (Anastopoulos and Pashalidis 2021) tested three different dyes (methylene blue, crystal violet, and malachite green), being that single-use surgical face masks acted as dye carriers in the aquatic environment. Due to their lipophilicity, MPs may adsorb and carry several contaminants (O’Donovan et al. 2018), such as pesticides, medicines, and oil, among others; emerging contaminants of concern such as polycyclic aromatic hydrocarbons, polychlorinated biphenyls, per-/poly-fluoroalkyl substances, due to their high superficial area (Joo et al. 2021; e Silva and de Sousa 2021). According to Joo et al. (Joo et al. 2021), MPs may play a role as a vector that carries hazardous microbes such as emerging bacterial threats (i.e., antibiotic resistant bacteria) and deadly viruses (e.g., coronavirus); this causes great concern over MPs contaminated with emerging contaminants. So, as MPs in the environment, the polluting power of face masks is even greater, since they may act as a medium for disease outbreak (Fadare and Okoffo 2020). Also, PPEs based on low-density polymers could serve as artificial substrates for rafting non-native or invasive species (colonization of invasive species) (De-la-Torre and Aragaw 2021; De-la-Torre et al. 2021), causing imbalance between species.

PPEs may have different fates and sinks depending on the characteristics of the raw materials, such as density. Materials less dense than water float, whereas the ones denser tend to sink (De-la-Torre and Aragaw 2021).

In the waters, animals and seabirds may die as a consequence of plastic ingestion. They are attracted by the movement and colors of plastic waste, ingesting them believing it is food (de Sousa 2020). Concerning MPs, they may be ingested by several aquatic biota especially the filter feeders, such as molluscs, mussels, and oysters, from where it enters the food chain and consequently could lead to physical and toxicological effects on aquatic organisms and human being as final consumers (Ogunola et al. 2018). Proving the consumption of MPs by humans, they were found in feces (Schwabl et al. 2019) and, in recent times, their presence was detected inside the human placenta as well (Ragusa et al. 2021). Not long ago, shocking news addressed the death of a Magellanic penguin. In its stomach, a face mask was found during the necropsy (Fig. 2), resulting in the cause of its death (2020).

When incorrectly disposed of in the organic fraction of municipal solid waste (OFMSW), the mask may interfere with the digestion process. De Albuquerque et al. (de Albuquerque et al. 2021) verified the influence of the presence of single-use face masks in high solids anaerobic digestion (HSAD) in waste management facilities. The results suggested that the presence of face masks in OFMSW negatively affected methane productivity and kinetics. In the digesters amended with face masks, the total cumulative methane production decreased by up to 18%, along with a 12–29% decrease in maximum methane production rates than the control digester (without face masks). The lag phases increased by 7–14%. After 40 days of mesophilic anaerobic digestion, the face masks remained undegraded. However, the worst finding of the authors is yet to come: microplastics released from face masks in digestate may amplify the transmission of antimicrobial resistance genes to our ecosystem via the land application.

Also, some authors argue about the environmental impacts of the textile industry (Karim et al. 2020), which largely contributes to the global CO_2 emission and global waste. Synthetic fibers, such as polypropylene, consume the highest amount of energy during fiber manufacturing, emit large amounts of greenhouse gas emission, and use large amounts of water. Due to hygienic concerns, infectious PPE waste is incinerated at high temperatures, which may emit toxic gases. To become environmentally sustainable, it is important to reuse and recycle textile materials.

Thus, the reader may think that a more environmentally appropriate form of protection is the use of cloth face masks. However, it is wrong to think that reusable cloth masks are completely environmentally friendly. Shruti et al. (Shruti et al. 2020) alert about the release of microfibers during washing of cloth masks. Additionally, when improperly disposed of in the environment, they cause damage in the same way as single-use face masks. Cloth masks represent a danger to marine organisms because they can get caught with the straps (Ardusso et al. 2021; De-la-Torre and Aragaw 2021) and, due to this, several campaigns ask people to cut the straps from the masks to avoid animals getting trapped in them (Ardusso et al. 2021). Furthermore, the textiles may have bactericidal, fungicidal, and antiviral properties and may contain nanoparticles such as Cu and Ag to combat pathogens, which may improve their polluting power since these nanoparticles are known as emerging contaminants.

Since they are contaminated, all the post-used face masks should be disposed of as clinical/hospital waste. Even so, these residues may be dangerous. Plastic is unlikely to be completely eliminated through burning and often leaves residues of nano- and micro-sized plastic particles, which are harmful both to the atmosphere and to the ecosystems they are introduced (Ahmadifard 2020). Also, incineration emits toxic gases (Celis et al. 2021).

In addition to all the contaminated hazardous residues generated from COVID-19 patients and hospitals, no less important are the residues generated from COVID-19 tests. The literature has shown that confirmatory testing for COVID-19 generated more than 15,000 tons of residues until August

Fig. 2 Magellanic penguin, found dead on a beach in the city of São Sebastião, north coast of São Paulo (Brazil), and the face mask found in its stomach. The use of the photo was authorized by the *Instituto Argonauta*

2020. Most of the tests are made of polypropylene, and they are incinerated due to their hazardous nature to humans, but toxic chemicals are released into the environment during the process (Celis et al. 2021). Additionally, this waste can be contaminated with SARS-CoV-2 and, therefore, can contribute to further spread if not managed properly (Das et al. 2021).

According to China local governments (ADB 2020), COVID-19 patients produce around 3.4 kg of contaminated waste per day when hospitalized. Medical waste soared from 45 to 247 tons during the outbreak (around six times higher) in China; in the most affected areas in France, the amount increased by 30–50%; and increased by 30% in Netherlands (Wei and Manyu 2020).

Medical waste also encompasses the general waste from hospitals with COVID-19 patients, such as food and dining boxes used by patients, general waste of suspected COVID-19 patients in quarantined areas, and infusion bottles and bags (usually disposed of by nurses for recycling) (Wei and Manyu 2020). During the hospitalization of my family member cited before, it was possible to observe the huge amount of residues generated per day. All food, cups, and cutlery that are not consumed or used by the COVID-19 patient cannot be used by someone else to prevent contamination and are thrown away. Also, each time nurses enter a patient's room, they need to wear a single-use apron, cap, and gloves that are discarded right after use.

Concerning the contaminated residues, their improper treatment poses serious risks of disease transmission to waste pickers, waste workers, health workers, patients, and the community in general through exposure to infectious agents since waste emits harmful and deleterious contaminants into society (Das et al. 2021). The increase in the amount of PPEs used by the population has enhanced the risk and magnitude of the problem. According to Das et al. (Das et al. 2021), the composition of healthcare solid waste during the COVID-19 pandemic is more or less similar to that produced in normal circumstances, except for the generation of a huge quantity of plastics/microplastics.

Another weak point posed by the COVID-19 pandemic is the increase in the environmental footprints of healthcare. The potential sources are PPEs; testing kits; energy consumption (building, equipment, etc.); disinfection, sterilization, hand sanitizers; food packaging/cutlery packs; and waste disposal/treatment; among others (Klemeš et al. 2020). So, plastic is a great contributor to this increase.

According to Urban and Nakada (Urban and Nakada 2021), besides public health and economic impacts, social isolation has also caused indirect environmental effects. The pandemic has brought with it a change of habits. Due to the social isolation imposed by the pandemic, buying over the Internet and apps has been a safe and viable option. The Mobills app analyzed more than 46,000 users from January to December 2020, showing an increase of 149% in delivery service in Brazil, concerning the three main delivery apps (Rappi, Ifood, and Uber Eats). Comparing December and March, the increase was 187% (Ribeiro 2021). Many sectors of the economy have joined online shopping, and most small business owners have found a way of not shutting down their businesses due to all the restrictions imposed by the pandemic. Almost everything can be acquired, combining security with the convenience of receiving the purchases without leaving home.

However, all items need to be packed to facilitate transportation and maintain the product quality, which has caused a significant increase in packaging production, both in the productive sector and as residues. This shift in solid waste production resulted in a huge environmental impact and a challenge for cities around the globe (Kalina et al. 2021; Tilley and Kalina 2020).

Figure 3 shows a supermarket purchase just after delivery at home, and a large number of packages can be observed. All products were packed in plastic bags. However, the cleaning products, each one packed individually, and all of them inside two plastic bags. The refrigerator products, in addition to being in plastic bags, were inside other closed plastic packages. Economic crisis forces businesses to tend to improve the quality of care at all stages, including delivery. The fact of separately packing each product can avoid possible leaks, as well as avoid contamination between different types of products, but the amount of waste generated is much greater. One question arises: Using less packaging, would the quality of the product or delivery be affected? Would the client be satisfied?

According to the São Paulo City Government, in Brazil (2021), the amount of common waste collection in 2020 compared to the previous year did not show significant variation, while the amount of selective collection showed an increase of 17.4% compared to the previous year. When compared to the quarantine period in 2020, from March to December, the amount of residues from selective collection increased by 20% when compared to the same period in 2019.

Leal Filho et al. (Filho et al. 2021) analyzed the impact of COVID-19 on people's consumption behavior around the world. Some interesting results were as follows:

- 45–48% of the respondents observed increased consumption of packed food, fresh food, and food delivery during the pandemic.
- 55% indicated an increase in waste generation during the lockdown period, being the highest increase observed for plastic packaging and food waste (53% and 45%, respectively).
- Just 32% indicated they have increased their efforts to segregate waste properly during the lockdown.

Fig. 3 A supermarket purchase just after delivery at home. All the products in plastic bags (i); the cleaning products, each one packed individually (ii), and inside two plastic bags (iii); and refrigerator products (iv)

- Waste management is associated with an increased amount of health and packaging waste by 45% of the respondents.
- 66% indicated the need for improving product design to use less packaging or to increase recyclability (61%).

The lasts results also demonstrate the increase in the production of recyclable materials at homes around the world and depict something worrisome: the lack of environmental awareness of most of the respondents. Even producing more recyclable residues at home, only 32% segregated them. On the other hand, they showed concern about the design of new packaging containing less plastic, which may be even contradictory.

Nevertheless, not all packaging from deliveries is effectively recycled. Most deliveries use packaging made of multilayer materials, expanded polystyrene, plastic film, or adhesive tape, all materials that are difficult to recycle and therefore, depending on the location, are considered rejects. Figure 4 shows the packages from an app delivery purchase. Fast foods are usually served using a large amount of packaging, many of them made from multilayer materials. These packages have a great potential to be considered rejects, even being made of recyclable materials, due to the difficulties of being effectively recycled.

On the other hand, the increase in the volume of recyclable materials did not result in increased recycling. The manual segregation in some recycling centers was suspended during the pandemic to avoid contamination. Urban and Nakada (Urban and Nakada 2021) assessed the environmental impacts caused by shifts in solid waste production and management due to the COVID-19 pandemic in Brazil. They analyzed data from 30 cities, representing a population of more than 53.8 million people, i.e., 25.4% of the Brazilian population. As a consequence of the suspension of recycling programs, considerable amounts of natural resources have not been saved over a month, such as 24,076 MWh of electric power, and 185,929 m^3 of potable water. Moreover, the total sale price for recyclable materials during the suspension of recycling programs reached more than 781 thousand dollars, being these materials disposed of in landfills demanding an extra volume of 19,000 m^3 (reducing landfill lifespan and hence causing a double loss: economic and environmental).

Fig. 4 Fast food purchased from an app delivery

There is no doubt that plastic plays an important role in our society, especially during pandemics as discussed throughout this work, but it may bring several problems. The current situation has proved that existing considerations of plastic waste management systems are inadequate (Haque et al. 2021). Also, the increased plastic pollution during the pandemic was aggravated by the lack of knowledge about the type of domestic waste generated and its deficient classification by people at home (Konda et al. 2020). "Although there has been significant progress towards COVID-19 vaccine developments, face masks will not go away immediately. Face masks will be remained as a part of our life for at least several more months. In addition to addressing immediate concerns regarding disposable face masks, this is an opportunity to develop innovative technologies for sustainable plastic waste management, an existing challenge for waste management industries" (de Albuquerque et al. 2021). In the sequence, some possible solutions to solve/reduce the problems which plastic may cause will be discussed.

Possible solutions

In this section, some possible solutions to solve/reduce the problematic of plastic pollution will be discussed, based on the recent literature.

The adoption of government regulations, in which restrictions on the use of plastic are imposed to the population, is an option. However, some policies restricting the use of single-use plastics (such as straws) were suspended, canceled, or postponed during the COVID-19 outbreak (da Costa 2021), given its importance to slow down the COVID-19 transmission, which led to questioning the role of plastic worldwide. Since the virus may remain active between 4 and 7 days in plastic (Chin et al. 2020; van Doremalen et al. 2020), concerns over the role of reusable plastics as vectors for SARS-CoV-2 virus contributed to the reversal of bans on single-use plastics (Prata et al. 2020). Several countries are examples of success in the implementation of measures to reduce the use of plastic as bans and imposed fees (Ogunola et al. 2018).

The correct management of waste is essential to avoid socio-environmental problems, especially during pandemics. COVID-19 waste may spread the virus if not handled properly (Kalina et al. 2021; Tilley and Kalina 2020). It must be correctly identified, segregated, disinfected, transported, and safely disposed of. However, the number of available incinerators is not sufficient to treat the tons of contaminated waste produced per day, especially in developing countries (Behera 2021).

Some authors point out as one of the possible solutions to the problem of the final disposal of residues the use of biodegradable plastics (Anderson and Shenkar 2021). Still, this option should be seen with caution, especially for plastic applications in the medical field. However, according to Celis et al. (Celis et al. 2021), this is a possibility in the case of plastics used for COVID-19 tests. "Long-term actions to reduce the environmental impacts of medical waste used with COVID-19 testing, must include the manufacture of biodegradable medical inputs free major compounds in smoke from burning plastics. Therefore, their decomposition would be faster in the case of inputs ended up in landfills, where they would not emit persistent toxic chemicals if they are incinerated" (Celis et al. 2021).

Nonetheless, in the case of packaging, no matter the raw material used in their production, i.e., if a fossil-fuel polymer or a biopolymer has been used, the packaging cannot be disposed of in inappropriate places. Some authors warn that, outside compost facilities and specifically in marine environments, bioplastics may have a similar effect to that of fossil fuel–based plastics (Anderson and Shenkar 2021). Anderson and Shenkar (Anderson and Shenkar 2021) investigated the effects of polyethylene terephthalate (PET) and polylactic acid (PLA) single-use cups and plates on a solitary ascidian's biological and ecological features. Both PET and PLA microparticles reduced the fertilization rate of *Microcosmus exasperatus*, as well as the accumulation rates in adult *M. exasperatus* exposed to micronized PET and PLA particles at two concentrations were similar for both materials.

Concerning the minimization of the negative impacts posed by plastic pollution in waters, especially pollution by MPs, the literature points out some possibilities, such as the application of membrane filtration (Joo et al. 2021). Other possibilities advised by the literature are physical sorption and filtration, biological removal and ingestion, and chemical treatments (Padervand et al. 2020).

All these options are possible solutions for water plastic pollution. All these options are possible solutions to reduce water pollution by plastic, always considering the reduction of plastic waste so that the problem does not get worse. Among the alternatives to reduce plastic pollution are an efficient waste management system, government regulations, public awareness, and environmental education. Actions related to 3Rs (reduce, reuse, recycle) must be encouraged, keeping in mind that the main idea is to reduce at the source whenever possible (de Sousa 2021). Decisions should be taken based on the literature and life cycle assessment results (Miller 2020).

There is no doubt about the benefits of recycling. With all the challenges posed by the COVID-19 pandemic, recycling should continue but, evidently, in a safe way. Thus, to avoid health problems for workers of the sector, healthy people must follow a protocol for the preparation of recyclable residues produced at homes: after using packages, they must be cleaned to remove the organic waste and stored in clean closed plastic bags or boxes for a period of 7 days before sending to the selective collection. By doing so, the survival time of the virus is exceeded, and the handling of the residues will be safer in the recycling sector (the possibility of indirect contamination is reduced, Fig. 1). Additionally, at the workplace, hygiene rules must be improved, such as the use of professional gloves and masks, frequent change and cleaning of PPEs and professional clothing, and frequent hand-washing (de Sousa 2020).

Even knowing that recycling is essential to the success of the circular economy, and also to alleviate the vast amount of plastics entering the oceans (Ogunola et al. 2018), "recycling efforts are not the panacea that many consumers assume... recycling does not erase any of the upstream impacts incurred throughout the resource extraction and manufacturing stages of the product" (Miller 2020). Therefore, it should be considered, but it is not a solution to all the problems that plastic may cause. It is important to have in mind that what is recyclable does not mean that it is effectively recycled. Many other aspects that go far from the scope of this work are considered so that a material can be recycled in a given location, such as contamination and market.

Concerning post-used PPEs, the literature presents some possible solutions as well.

According to de Albuquerque et al. (de Albuquerque et al. 2021), an environmentally benign solution to divert digestate having face masks from the landfill or land application can be the result of thermochemical conversion processes (e.g., pyrolysis, gasification). Jung et al. (Jung et al. 2021) suggested an environmentally benign process: CO_2 was used as a reaction medium for pyrolysis of the single-use face mask, resulting in the production of H_2 and various ranges of hydrocarbons. Purnomo et al. (Purnomo et al. 2021) reviewed the main thermochemical conversion technologies available for the conversion of COVID-19-related medical wastes (CMW). Incineration, gasification, and pyrolysis are considered able to facilitate the conversion of a wide range of medical waste types. Torrefaction is considered suitable for pretreatment, before being further converted through other conversion methods. Furthermore, CMW can be disinfected first by using several methods including sanitized refuse-derived fuel and, doing so, it is possible their coprocessing with ordinary solid waste. From these processes, part of the energy used in the production of the PPEs (being that they are a great contributor to the increase in the environmental footprints of healthcare (Klemeš et al. 2020)) can be recovered and the footprint can be mitigated.

Rowan and Laffey (Rowan and Laffey 2021) reviewed some possibilities of reprocessing PPEs using dry and moist heat, ozone, hydrogen peroxide vapor, ethylene oxide, and ultraviolet light, being that all of them showed satisfactory results in the inactivation of SARS-CoV-2 virus. The literature (Parashar and Hait 2021; Patrício Silva et al. 2021) points that the effective decontamination for reprocessing of PPEs is a significant issue to reduce plastic waste generation,

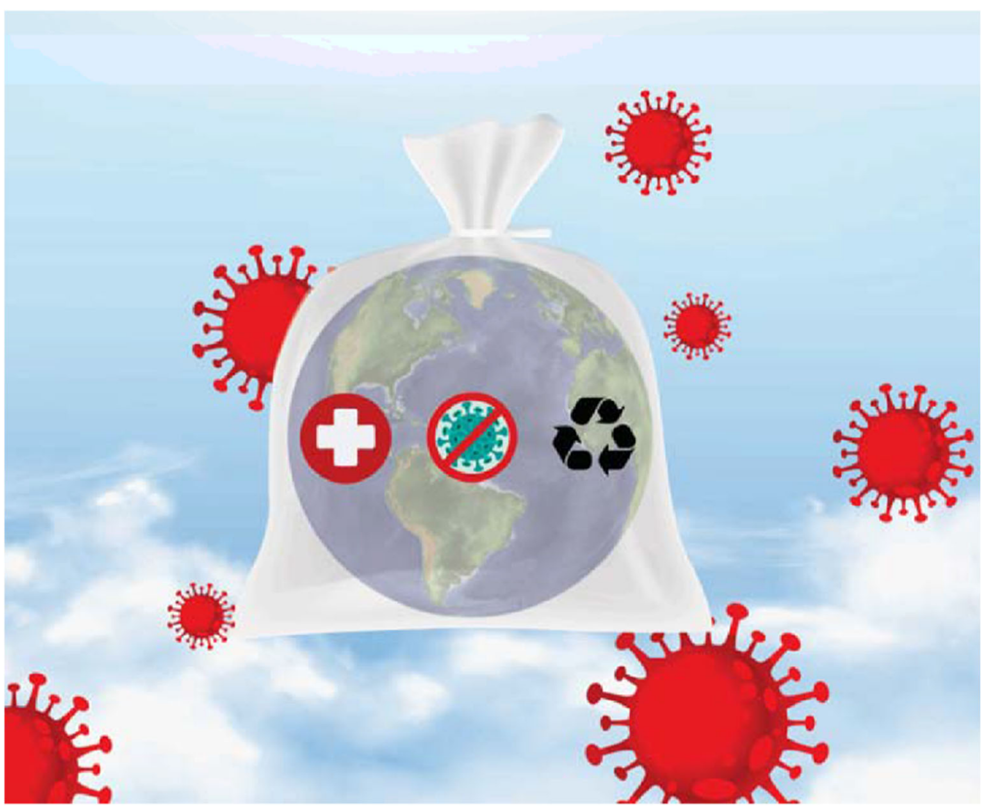

Fig. 5 Schema showing the role of plastic against the SARS-CoV-2, the coronavirus responsible for COVID-19

by using ultraviolet light, ozone, or bioengineering approaches, among others.

A French industry is recycling post-used single-use face masks, transforming them into a plastic-like material, which can be used in the production of several objects (2020). Firstly, the masks are collected and placed in "quarantine" for 4 days, being then ground down into small pieces and subjected to ultraviolet light to ensure they are completely decontaminated, and mixed with a binding material during processing. Finally, the recycled material is ready to be used as raw material in the manufacture of other objects, such as part of face shields. Since June 2020, more than 50,000 masks were recycled.

To reduce contaminated waste, regarding post-used PPEs, a possibility is the design of new reusable models, with lower energy consumption. However, a proper design standard, material selection, and user guideline are needed to ensure its effectiveness (Klemeš et al. 2020).

Concerning disposable syringes used in the vaccination of the population against the COVID-19 which are generating huge amounts of residues worldwide, some authors discuss some recycling possibilities, such as the recycling of needles (Ahmed et al. 2018) and plastic syringes (Hassan et al. 2019) in the production of fiber-reinforced concrete and incineration treatment (Ghodrat and Samali 2018).

The pandemic is not over yet, and activities are slowly returning to "new" normality in some countries. Nevertheless, an increase in the number of new cases has been observed in many countries, resulting in restrictions even more severe than those suffered at the beginning of the pandemic. In this sense, can the knowledge acquired so far be used aiming at the safety of workers of the recycling sector. And can, after this pandemic is overcome, academy and society use the knowledge and wisdom acquired towards the truly sustainable development for the health of the population, by consciously using and correctly disposing of plastic and focusing on the circular economy.

It is indispensable to urgently find a common point in discussions related to plastic, involving the environment, health, and economy. The benefits of using plastic are indisputable, especially during a pandemic, as it is considered a life savior. However, it becomes a polluter when improperly disposed of, resulting from the irresponsible action of people. So, it is not enough to create laws or suspend the existing ones to restrict its use, it is necessary to educate, inform, extend the producer responsibility and, most importantly, raise awareness of the population. Only in this way can each person fulfill his role in the society for the common interest.

Figure 5 schematically presents the role of plastic against the SARS-CoV-2 virus. Even its role being on proof, it is an important ally in the struggle against the virus.

Acknowledgments The author would like to thank Bruna Marcelle Bastos de Sousa for the invaluable help in the production of the scheme presented in this work and for the pictures. This work is dedicated to my beloved mother, who lost the battle against COVID-19 and passed away during the review of this work. Even in her last moments, she contributed to the conclusion of this work, showing me all the equipment that kept her alive, which were used as examples of the importance of plastic during the COVID-19 pandemic. Wherever she is, she remains alive in my memory, inspiring me as she always has in her brief existence. Elizabete Moreira Bastos de Sousa (*in memoriam*), mother, thank you for the valuable heritage that left me: your teachings and example of life.

Availability of data and materials Not applicable.

Author contribution F. D. B. de Sousa wrote and proofread the manuscript for language editing.

Declarations

Consent to participate and publish The author participated in writing and agreed to publish in Environmental Science and Pollution Research.

Conflict of interest There are no conflicts to declare.

Disclosure The manuscript was submitted solely to Environmental Science and Pollution Research and no part of it was published or submitted anywhere else.

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