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Microplastics and Macroplastic Debris as Potential Physical Vectors of SARS-CoV-2: A Hypothetical Overview with Implications for Public Health

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Abstract: COVID-19, caused by SARS-CoV-2, was declared a global pandemic on 11 March 2020 by the World Health Organization. The pandemic has triggered an unprecedented increase in the production, consumption and disposal of multiple types of plastic-based personal protective equipment (PPE) as a measure to reduce the infection. Recent research shows that plastic surfaces can serve as a fomite for coronavirus transmission as it can remain stable and be viable on polypropylene for up to 72 h or on other plastic surfaces for up to 9 days. While it is unknown whether or to what extent macroplastic debris and ubiquitous microplastics emitted into the environment can serve as physical vectors or fomites of pathogenic viruses, recent studies have reported that both macroplastic and microplastics can serve as vectors for harmful pathogens and invasive species (biological pollution). Here, hypothetical scenarios based on the weight of evidence are proposed to plausibly state the role of plastic debris (e.g., single-use-plastics), discarded PPE supplies, including facemasks, sanitizer bottles, gloves, and plastic bags, as well as microplastics as potential physical vectors of SARS-CoV-2, serving as a route of exposure to humans and wildlife in the terrestrial, freshwater and marine ecosystems.

Keywords: microplastics pollution; macroplastic debris; personal protection equipment (PPE); single-use plastics; physical vector; SARS-CoV-2; COVID-19 pandemic; airborne transmission; wastewater; public health

1. Introduction

Oceans pollution by marine plastics and microplastics is a persistent marker of the ecological footprint of humans in the Anthropocene era, posing an urgent health risk for all the world's oceans and coastal seas [1]. In the age of plastics, ocean plastic emissions from 192 coastal countries (i.e., equivalent to 93% of the world's population) have ranged from ~5 to ~13 million metric tons per year, averaging ~8.75 million tons yr^{-1} [2]. At present, the amount of plastics in the oceans has been estimated to be around 75–199 million tons [1]. Recent studies estimated that while there are 5.25 trillion plastic pieces equivalent to a minimum weight of 268,940 tons floating in the global ocean [3], the ocean bottom harbors microplastics hotspots of up to 1.9 million pieces m^{-2} [4]. Thus, in terms of persistence and ubiquity, marine plastics and microplastics present a serious threat to all marine life, while also impacting human health and well-being.

Additional environmental health stressors and a global public health threat were introduced since COVID-19 was declared a global pandemic by the World Health Organization on 11 March 2020 [5]. COVID-19 is caused by SARS-CoV-2, a novel coronavirus responsible for generating severe acute respiratory syndrome (SARS) in humans. In late January 2022, there were ~376 million confirmed total cases of COVID-19 with ~5,670,000 deaths in the world and close to 10 billion vaccine doses administered, according to the real time-interactive database from the John Hopkins University's Coronavirus Resource Centre (https://coronavirus.jhu.edu/map.html (accessed on 6 November 2021); [6]). These figures indicated an infection fatality rate of 1.5% worldwide (i.e., calculated as the number of deaths due to COVID-19 divided by the total number of confirmed coronavirus cases).

Of great concern is the unprecedented demand for single-use plastics and massive use of personal protection equipment (PPE; Figure 1). The use of facemasks, gloves, packing and empty sanitizer bottles for health care and frontline workers and public safety [7–9] has grown exponentially, following public health recommendations or requirements to prevent the spread of the virus since the onset of the COVID-19 pandemic in early 2020 and ongoing new emerging variants (e.g., delta, omicron). Poor PPE waste disposal and critical hazardous waste and public health management issues are of paramount concern [8–10]. One study estimated an average of 8.4 million tons of COVID-19 pandemic-associated plastic has been generated from 193 countries as of 23 August 2021, from which close to 26 thousand tons were released into the global ocean [7]. Almost all nations around the world followed the public health protection guidelines and rolled back single-use plastic bans temporarily, resulting in a surge of plastic pollution symbolized by the amount of PPE that has been littered in the coastal and marine environment.

Figure 1. Discarded personal protection equipment (PPE) as a consequence of the COVID-19 pandemic, which prompted and caused the massive demand, production, overuse and misuse of PPE-plastic waste and pollution: (**a**) blue, medical facemask black (see white arrow) entangled in a white mangrove tree branches (*Laguncularia racemosa*); (**b**) plastic (non-medical) facemask observed (see white arrow) on red mangrove leaves (*Rhizophora* sp.) in coastal waters of the Puerto Ayora, Santa Cruz Island, Galápagos (Ecuador); (**c**) blue medical mask discharged on storm drain/sewer (BC, Canada), and; (**d**) a pair of surgical blue gloves dumped close to a sidewalk (BC, Canada). Photo credits: (**a**) K. McMullen (Galápagos); (**b**) J.J. Alava (Galápagos) and (**c**, **d**) N. Alava (Burnaby, BC, Canada).

The human transmission of SARS-CoV-2 is mainly through respiratory secretions disseminated by direct exposure to floating droplets containing the virus after being ejected through the air from infected people when exhaling, sneezing, or coughing [11]. When aerosolized into fine, floating particles, the SARS-CoV-2 can float in aerosol droplets (<5 µm) and be viable for three hours, remaining infectious [11], but also it can remain viable longer than three hours due to the prolonged residence times in the air as a potential route for airborne transmission [12–14]. Both outdoor and indoor airborne [12–16] and fomite (e.g., plastics, metals) transmissions [9,11,12,17] are known mechanisms of coronavirus dissemination. Human coronaviruses like the Severe Acute Respiratory Syndrome (SARS) coronavirus (i.e., SARS-CoV), for example, possess the capacity to persist on plastic surfaces from 4 up to 9 days [17–19].

Wastewater, untreated water and freshwater were also underscored to be a potential source and exposure route of transmission and infection for COVID-19 as confirmed by the detection of SARS-CoV-2 viral particles in waterways [20–24]. Yet, questions remain regarding the potential role of these types of water and seawater to disseminate the virus in water systems of rural, urban, industrial and coastal marine environments polluted with microplastics (<5 mm) and macroplastics (>5 mm). In this hypothetical overview, we argue and focus on the influence of macroplastic debris and microplastics as environmental contaminants serving as plausible vectors of SARS-CoV-2 with implications for public health by stating a hypothesis, based on the weight of evidence and the scientific literature. As a baseline, recommendations to prompt grand challenge research fronts to better understand the virus transmission to humans in the multi-media aquatic or marine environments facing global plastic pollution with implications for public health are suggested.

2. Microplastics as Vectors of SARS

Previous studies have shown that the persistence of SARS-CoV on plastic surfaces can last a maximum of 9 days [17,19]. Conversely, new research shows that the COVID-19 viral particles (i.e., SARS-CoV-2) are also able to remain stable and viable up three days (72 h) on a common type of single-use plastic (i.e., polypropylene [PP]) and stainless-steel surfaces, while on a copper surface, it can remain four hours [11]. SARS-CoV-2 possesses the longest viability on plastic with an estimated median half-life of the virus of approximately 6.8 h (95% CI: 5.62−8.17) on it; however, the virus titer load is greatly reduced after 72 h on a plastic surface, i.e., from $10^{3.7}$ to $10^{0.6}$ 50% tissue-culture infectious dose [$TCID_{50}$] per milliliter of medium [11]. This finding highlighted the role of plastics as potential physical vectors of coronaviruses with the capacity to readily transmit the virus to humans. In light of the aforementioned data, what are the implications of plastics/microplastics as SARS-CoV-2 vectors for marine ecotoxicology, environmental toxicology and public health science; and what is their potential impact on our capability to assess exposure and hazard risks to marine fauna, terrestrial wildlife and humans?

While it is unknown whether or to what extent macroplastic debris and microplastics can serve as physical vectors or fomites of photogenic viruses, recent studies have reported that both macroplastic and microplastics can serve as vectors for harmful pathogens and invasive species (i.e., biological pollution). Particularly, the existence of microorganisms and microbial communities or biofilms inhabiting the surface of microplastics, referred to as Eco-corona [25] or Plastisphere [26], harboring a biodiverse epiplastic community and plastic biofilms has been discovered, recently [27–32]. In fact, several molecular studies have consistently revealed a wide range of epiplastic microbial groups [27–29]. As part of the epiplastic communities, microplastics can carry on their surfaces—pathogenic bacteria such as *Vibrio*, *Aeromonas*, *Enterobacter*, *Halomonas*, *Mycobacterium*, *Photobacterium*, *Pseudomonas*, *Rhodococcus*, and *Shigella*, as well as fungi, i.e., Pestalotiopsis [27,29], underscoring the potential role of plastic particles with associated biofilms as fomites and vectors of pathogens.

The ubiquitous nature and capacity of microplastics as hazardous waste and diverse contaminant group [33,34] to serve as chemical and pathogen vectors must be seriously considered as part of the overall ecotoxicological risk assessment of human exposure and microplastic safety [35,36]. It is well known that viruses such as coronaviruses (e.g., SARS-CoV-2) live and replicate inside living cells with their multiproliferation mechanisms and are expelled at cells death in liquid droplets via sneezing and coughing as mucus and saliva along with other more abundant microorganisms inhabiting the respiratory tract and oral system, including other viruses, bacteria, and fungi [37]. Notwithstanding, the capacity of macroplastic debris and microplastic to serve as physical vectors to harbor and transport viruses and their variants (e.g., contagious coronaviruses, delta, omicron) has not been investigated. SARS-CoV-2 may well be part of the biofilm sustaining the Plastiphera or Eco-corona present or stuck on the microplastics surface or coating. Moreover, plastic additives or components and plasticizers were also suggested as water pollutants likely able to exhibit the potential to exacerbate COVID-19 respiratory symptoms, pending the pursuit of epidemiological research still required to confirm the synergistic effects between these pollutants and the virus [38]. Thus, a call out for ecotoxicological risk assessments, including exposure and dose-effect experiments in tandem with the guidance of public health research, is indeed needed to address these questions.

3. Hypothetical Reference Point and Weight of Evidence for Grand Challenge Research

Hypothetically, two plausible theoretical scenarios are at least postulated and under which microplastics can be attributed as potential physical vectors for the transmission of SARS-CoV-2 to people and animals [39] in the multi-media environment, including terrestrial, aquatic or marine ecosystems. As shown in Figure 2, these hypothetical scenarios can be described as follows:

3.1. Exhalation and Inhalation in the Presence of Microparticles

The presence of plastic particles residing temporarily in the air as part of aerosols or suspended particulate matter are likely to be spiked by microdroplets carrying the virus. Microdroplets are greater respiratory droplets (e.g., up to 1 mm) generated from sneezing, coughing and exhalation (i.e., aerosolization of virus from normal breathing) by an infected human either symptomatic or asymptomatic, as SARS-CoV-2 can be shed by people even before the development of symptoms [12–15]. Thus, as SARS-CoV-2 can linger for three hours in aerosol droplets, the suspended microplastics or microfibers can become recipients and physical vectors for the virus by transporting it further away (i.e., dry or/and wet deposition) on the plastic surface [11,17–19]. These microplastic particles can eventually be exposing and contaminating another person via inhalation or direct intake of airborne particles. People are also exposed to plastic particle surfaces contaminated with SARS-CoV-2 through an infected person exhalating, coughing or sneezing. These exposure pathways are based on the virus viability and persistence on plastic surfaces within 72 h [11] and from 96 [18] to 216 h [19].

Humidity and temperature can also dictate the airborne transmission of coronaviruses. As this scenario is based on the exposure to the virus outside under given atmospheric conditions in an external environment, humidity and the amount of virus particles present in concert with the concentration of microfibers floating in the air can play an important role by influencing the virus exposure and transmission.

3.2. Dermal Contact and Ingestion in the Presence of Plastic Particles

As gravity lands these droplets within 1 or $\geq$2 m, they deposit the virus on surfaces (e.g., plastics surfaces; [11]), from which people can pick it up and infect themselves by touching their mouth, nose, or eyes. Equally, some SARS-CoV-2-contaminated microplastics resulting from the assumed scenario aforementioned are subsequently transported via air-deposition (i.e., dry or/and wet deposition) through airborne spread and transmission [14,15] and run-off; and, then deposited on soil or as buoyant plastic particles, floating on freshwater or seawater. As the SARS-CoV-2 can remain viable on plastic surfaces within 72 h [11] with a maximum persistence of 216 h or 9 days [17,19], microplastics or large plastic debris (e.g., face masks, gloves) could serve as potential vessels to carry the coronavirus, eventually contaminating people, and marine-coastal wildlife (e.g., marine mammals and domestic animals or land mammals [39]) exposed to these macro and microplastics. Two possible outcomes for the risk of exposure could take place from this hypothetical scenario (Figure 2):

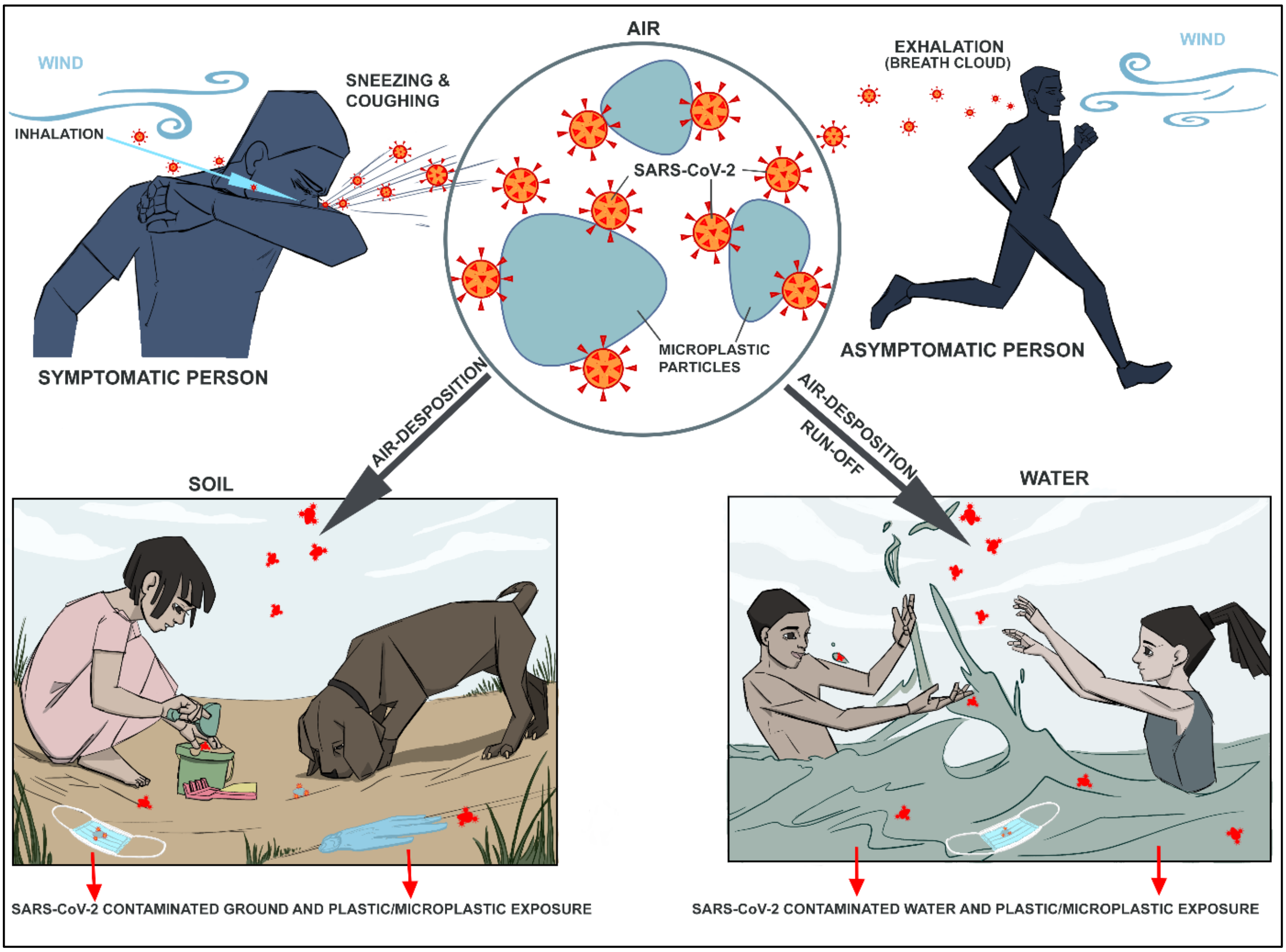

Figure 2. Humans are likely to be exposed to SARS-CoV-2-contaminated microplastic through two possible pathways of exposure. (1) Exhalation and inhalation (**top**): airborne SARS-CoV-2-contaminated microplastics, previously spiked by exhalation (breath cloud) from a transitory or running asymptomatic or unvaccinated person within a period of three hours, can accidentally be inhaled by an uninfected individual passing by, or from a symptomatic or asymptomatic person (either vaccinated or unvaccinated) sneezing and/or coughing can spike microplastics or plastic surfaces that eventually can be transported far away by air and deposited through dry or wet deposition. (2) Dermal contact and ingestion (**bottom**): SARS-CoV-2-contaminated plastic items (disposable facemasks, gloves) and/or microplastics deposited on soil (e.g., sand, clay and sediments) and floating on water (e.g., recreational fresh or marine water) can serve as physical vectors or tiny fomites of the virus for up to 72 h, potentially transmitting the virus to people (e.g., children and adults) and pets in direct dermal contact with the soil by playing with dirt/sand or by indirectly ingesting it; and, swimming/bathing in natural or untreated recreational freshwater (rivers or lakes) or coastal locations (beaches) via direct water intake (i.e., accidental ingestion of water containing the contaminated plastic particles through the nose or mouth). Artwork: N. Alava.

(i) On the soil, toddlers, children and pets playing with dirt and sand on playgrounds, parks and beaches may be more vulnerable as they can swallow and be in direct dermal contact with soil or plastic items (disposable face masks, gloves) containing SARS-CoV-2-contaminated plastic surfaces/microplastic.
(ii) In the water (i.e., natural freshwater and untreated recreational water, ocean and coastal waters), people or beachgoers and animals swimming and splashing water can be in direct contact with SARS-CoV-2-contaminated microplastics when splashing and playing with water or when swallowing up small amounts of water containing these contaminated particles that can be deviated to and in taken via upper respiratory track or nasal airways, accidentally.

In addition to these exposure risk pathways in the multi-media environment, microplastics could aid in the transmission of COVID-19 at the household level, especially when in close contact with an infected person (e.g., asymptomatic or unvaccinated) sharing fibrous materials (e.g., textiles, fabrics, apparel/clothing items) such as clothes, blankets, coversheets, dish and bath towels, which are materials that readily emit microfiber plastic particles and likely to contribute to the virus transmission.

4. SARS-CoV-2 Contamination of Water and Interaction with Microplastics Pollution

While there is no evidence that SARS-CoV-2 can be transmitted and spread to humans through the use of pools, hot tubs and water play areas (i.e., due to disinfection with chlorine and bromine) or for drinking tap water, as most municipal drinking water treatment systems should remove or inactive the virus through filtration and disinfection methods [40], the long stability and lasting viability of the virus in plastic debris and microplastic present on untreated recreational or natural freshwater (e.g., rivers and lakes), run-off/storm-water, sewage/wastewater and seawater cannot be ruled out. This argument is of particular concern as the detection of SARS-CoV-2 RNA in untreated wastewater and freshwater has actually been demonstrated in several countries, including Australia, France, the Netherlands and the United States, as well as in developing countries with low sanitation levels, including Ecuador [20–24,39,41–43]. While the plausible detection of SARS-CoV-2 in seawater has yet to be investigated, both the presence and infectivity of this virus have already been demonstrated in rivers or freshwater [24,43].

Moreover, the abundance, density and concentration of microplastics and nanoplastics particles as contaminants of emerging concern in wastewater and freshwater systems [44,45], mainly resulting from the degradation and fragmentation of macroplastic debris in inland waters [45], may well influence the interaction and viability between SARS-CoV-2 and plastic particles and thus the potential toxicological dose and exposure to humans and animals.

In this context, if this virus is indeed viable and stable in wastewater, the possible role of discharged plastic items and microplastics as anthropogenic contaminants to serve as vectors of SARS-CoV-2 in sewage or wastewater influent and effluent is viable, as wastewater treatments plants (WWTPs) can readily release billions of microplastics even after conventional treatments [44]. In fact, an estimated 30 billion plastic particles can be emitted from a single WWTPs near the ocean [44]. This kind of emissions highlights the pollution risks of microplastic exposure to marine biota and coastal communities.

The massive increase in PPE use and subsequent discharging and littering of discarded PPE supplies (personal, household and medical waste; Figure 1) including both medical and non-medical facemasks, gloves, and empty sanitizer bottles not only disrupted plastics' life cycles and exacerbated aquatic or marine plastic pollution [7–10], but also allowed for the emergence of PPE-plastic debris and microplastics as a source of contamination that can potentially transmit SARS-CoV-2 [8,10]. PPEs are mostly complex materials made of diverse synthetic non-degradable polymers and may well serve as vectors and sources of chemical contaminants (metals and organic compounds) interacting with plastic surfaces and becoming sorbed by means of one or multiple sorption mechanisms, such as electrostatic interactions, hydrophobic interactions, among others.

As an intra-pandemic plastic pollution problem at the global level, external contamination with these plastic types potentially carrying SARS-CoV-2 from infected and unvaccinated people is possible and cannot be ruled out. Thus, concerted ecotoxicological research fronts and biomedical monitoring to investigate the intertwined and combined impact of plastic pollution and SARS-CoV-2 are vital for environmental and public health.

5. Discussion and Recommendations

The oceans, marine biodiversity and coastal human communities, relying strongly on traditional seafoods, are affected by the pervasive plastic footprint and microplastic pollution. The origin of most discarded plastics is derived from anthropogenic activities and land-based sources, including urban areas, household, wastewater and industrial water, as well as fisheries, aquaculture, shipping, and tourism [1,2,7,41–48]. According to the recent global assessment of marine litter and plastic pollution by the UNEP [1], the chronic emissions of plastic waste into aquatic ecosystems are projected to nearly triple by 2040, if meaningful actions are not implemented.

The COVID-19 pandemic has aggravated the anthropogenic emissions of plastic waste and pollution, which is becoming a wicked problem. Should an impetus come forward to conduct lab and field studies to test the role of macroplastic and microplastics as artificial vessels for SARS-CoV-2, the new research fronts could consider several other types of plastics to assess the viability, half-life time and decay rate of the virus, including common plastic used on a daily basis.

Namely, plastic polymer types to further test their capacity to function as SARS-CoV-2 vectors or fomites can include polyethylene terephthalate (PETE), Polyester (PE), Polystyrene (PS) and Polyvinyl Chloride (PVC), Low Density Polyethylene (LDPE), High Density Polyethylene (HDPE), Polyurethane (PUR), and Expanded Polystyrene (EPS) foam or Styrofoam [49]. These plastic categories are used to manufacture products for single-use applications (i.e., disposable facemasks, and single-use plastics), including items intended to be used only once before they are thrown away such as grocery bags, food packaging, bottles, straws, containers, cups and cutlery [49,50]. In particular, LDPE, HDPE, PP, and PETE are among the most heavily utilized plastics' polymers, accounting for approximately 67% of the production of non-fiber plastics, followed by PVC, which is widely used as a construction material [50].

Comparing the stability and viability of SARS-CoV-2 on the surface of buoyant microplastics by particle size and polymer types floating on freshwater versus those floating on seawater during exposure experiments under different ambient and controlled abiotic conditions (e.g., temperature, ambient humidity or vapor pressure, pH, UV-irradiation, photo-oxidation;), and biotics factors (i.e., microbial and enzymatic activity) contributing to biodeterioration, biofragmentation and assimilation (i.e., when organism metabolizes the monomers into biomass, carbon dioxide, and water) [51] should be assessed.

Questions also remain on the infectious dose or load of the virus required on microplastics surfaces, to which humans or animals would potentially be exposed, so as to facilitate transmission and induce infection. For instance, if there are only a few microplastic particles around an infected person, can the infectious viral dose on the microplastic particle be enough to infect an individual?

In view of this accelerated rate of global pollution by plastics, exacerbated by the current COVID-19 pandemic, the pursuit of grand challenge research in tandem with concerted solid waste management actions and proactive public health strategic actions are needed to hamper and eliminate not only plastic pollution, but to mitigate and halt the potential COVID-19 transmission and infection through plausible dermal contact with contaminated plastic surfaces (e.g., PPE littering, including disposable facemasks and gloves), and undetected inhalation and accidental ingestion of microplastics, following the precautionary principle. This is of critical consideration as healthcare researchers seem to now be advocating for the use of plastic surgical masks, an argument that has increased during the emergence of the omicron variant in late 2021, rather than the use of reusable double-layered cotton facemasks. Spray-simulation research shows that cloth facemasks or covers effectively reduce the contamination of the environment by COVID-19 or coronavirus-contaminated liquid droplets [37].

To commence a treatment plan for the increase in plastic and microplastic pollution during the COVID-19 pandemic as well as the ongoing massive use of PPE, it is important to adopt and foster risk assessment frameworks, bioengineering-technology, governance strategies and feasible bans to mitigate and eradicate macroplastics (e.g., single-use plastics) and microplastic pollution from the coastal-marine environments as documented elsewhere [7,8,10,48,50–55]. Nonetheless, it is also imperative to assess and address the inequalities in who causes plastic pollution, who experiences and who are the recipients of the health impacts and consequences, and who can fix it by providing solutions along with those who have the political will to make the decisions and call for actions to divorce from a plastic dependence and foster more proactive life cycle assessments (i.e., from the extraction of raw materials to legacy plastic pollution) with agreements at the international level [55]. In this context, the people exhibiting high consumption rates of plastics steaming from a pervasive plastic demand and those who supply it disproportionately affect the success or failure of plastic pollution mitigation and solutions for marginalized societies and minority groups affected by the COVID-19 health crisis and the most exposed people in coastal communities under the siege of ocean plastics pollution.

6. Conclusions

Plastic pollution and the COVID-19 pandemic are intertwined in the Anthropocene. Discarded PPE and microplastics could play a role in potential coronavirus exposure and transmission in contaminated aquatic and marine environments and coastal zones with low sanitation standards. By fostering new collaborative studies and interdisciplinary research frameworks aimed to contribute to solutions-oriented research, it is imperative to champion the health and environmental protection needs of people living in coastal, rural, and remote communities in tandem with environmental programs to ensure equal access to hygiene, public health, and pollution prevention measures for a healthy ocean environment and oceans free of plastics in the face of the COVID-19 pandemic.

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References

1. UNEP. *From Pollution to Solution: A Global Assessment of Marine Litter and Plastic Pollution*; UNEP: Nairobi, Kenya, 2021. Available online: https://www.unep.org/resources/pollution-solution-global-assessment-marine-litter-and-plastic-pollution (accessed on 6 November 2021).
2. Jambeck, J.R.; Geyer, R.; Wilcox, C.; Siegler, T.R.; Perryman, M.; Andrady, A.; Narayan, R.; Law, K.L. Plastic waste inputs from land into the ocean. *Science* **2015**, *347*, 768–771. [CrossRef]
3. Eriksen, M.; Lebreton, L.C.M.; Carson, H.S.; Thiel, M.; Moore, C.J.; Borerro, J.C.; Galgani, F.; Ryan, P.G.; Reisser, J. Plastic pollution in the world's oceans: More than 5 trillion plastic pieces weighing over 250,000 tons afloat at sea. *PLoS ONE* **2014**, *9*, e111913. [CrossRef]
4. Kane, I.A.; Clare, M.A.; Miramontes, E.; Wogelius, R.; Rothwell, J.J.; Garreau, P.; Pohl, F. Seafloor microplastic hotspots controlled by deep-sea circulation. *Science* **2020**, *368*, 1140–1145. [CrossRef] [PubMed]
5. WHO. WHO characterizes COVID-19 as a pandemic. In *Rolling Updates on Coronavirus Disease (COVID-19)*; World Health Organization: Geneva, Switzerland, 2020. Available online: https://www.who.int/emergencies/diseases/novel-coronavirus-2019/events-as-they-happen (accessed on 21 March 2020).
6. Dong, E.; Du, H.; Gardner, L. An interactive web-based dashboard to track COVID-19 in real time. *Lancet Infect. Dis.* **2020**, *20*, 533–534. [CrossRef]
7. Peng, Y.; Wu, P.; Schartup, A.T.; Zhang, Y. Plastic waste release caused by COVID-19 and its fate in the global ocean. *Proc. Natl. Acad. Sci. USA* **2021**, *118*, e2111530118. [CrossRef]
8. Canning-Clode, J.; Sepúlveda, P.; Almeida, S.; Monteiro, J. Will COVID-19 containment and treatment measures drive shifts in marine litter pollution? *Front. Mar. Sci.* **2020**, *7*, 691. [CrossRef]
9. De-la-Torre, G.E.; Pizarro-Ortega, C.I.; Dioses-Salinas, D.C.; Ammendolia, J.; Okoffo, E.D. Investigating the current status of COVID-19 related plastics and their potential impact on human health. *Curr. Opin. Toxicol.* **2021**, *27*, 47–53. [CrossRef] [PubMed]
10. Klemeš, J.J.; Van Fan, Y.; Tan, R.R.; Jiang, P. Minimising the present and future plastic waste, energy and environmental footprints related to COVID-19. *Renew. Sustain. Energy Rev.* **2020**, *127*, 109883. [CrossRef]
11. Van Doremalen, N.; Bushmaker, T.; Morris, D.H.; Holbrook, M.G.; Gamble, A.; Williamson, B.N.; Tamin, A.; Harcourt, J.L.; Thornburg, N.J.; Gerber, S.I.; et al. Aerosol and Surface Stability of SARS-CoV-2 as Compared with SARS-CoV-1. *N. Engl. J. Med.* **2020**, *382*, 1564–1567. [CrossRef]
12. Greenhalgh, T.; Jimenez, J.L.; Prather, K.A.; Tufekci, Z.; Fisman, D.; Schooley, R. Ten scientific reasons in support of airborne transmission of SARS-CoV-2. *Lancet* **2021**, *397*, 1603–1605. [CrossRef]
13. Heneghan, C.; Spencer, E.; Brassey, J.; Plüddemann, A.; Onakpoya, I.J.; Evans, D.H.; Conly, J.M.; Jefferson, T. SARS-CoV-2 and the role of airborne transmission: A systematic review. *F1000Research* **2021**, *10*, 232. [CrossRef]
14. Morawska, L.; Milton, D.K. It Is Time to Address Airborne Transmission of Coronavirus Disease 2019 (COVID-19). *Clin. Infect. Dis.* **2020**, *71*, 2311–2313. [CrossRef] [PubMed]
15. Morawska, L.; Cao, J. Airborne transmission of SARS-CoV-2: The world should face the reality. *Environ. Int.* **2020**, *139*, 105730. [CrossRef]
16. Morawska, L.; Tang, J.W.; Bahnfleth, W.; Bluyssen, P.M.; Boerstra, A.; Buonanno, G.; Cao, J.; Dancer, S.; Floto, A.; Franchimon, F.; et al. How can airborne transmission of COVID-19 indoors be minimised? *Environ. Int.* **2020**, *142*, 105832. [CrossRef] [PubMed]
17. Kampf, G.; Todt, D.; Pfaender, S.; Steinmann, E. Persistence of coronaviruses on inanimate surfaces and their inactivation with biocidal agents. *J. Hosp. Infect.* **2020**, *104*, 246–251. [CrossRef]
18. Duan, S.M.; Zhao, X.S.; Wen, R.F.; Huang, J.J.; Pi, G.H.; Zhang, S.X.; Han, J.; Bi, S.L.; Ruan, L.; Dong, X.P.; et al. Stability of SARS coronavirus in human specimens and environment and its sensitivity to heating and UV irradiation. *Biomed. Environ. Sci.* **2003**, *16*, 246–255. [PubMed]
19. Rabenau, H.F.; Cinatl, J.; Morgenstern, B.; Bauer, G.; Preiser, W.; Doerr, H.W. Stability and inactivation of SARS coronavirus. *Med. Microbiol. Immunol.* **2005**, *194*, 1–6. [CrossRef] [PubMed]
20. Ahmed, W.; Angel, N.; Edson, J.; Bibby, K.; Bivins, A.; O'Brien, J.W.; Choi, P.M.; Kitajima, M.; Simpson, S.L.; Li, J.; et al. First confirmed detection of SARS-CoV-2 in untreated wastewater in Australia: A proof of concept for the wastewater surveillance of COVID-19 in the community. *Sci. Total Environ.* **2020**, *728*, 138764. [CrossRef] [PubMed]

21. Lodder, W.; de Roda Husman, A.M. SARS-CoV-2 in wastewater: Potential health risk, but also data source. *Lancet Gastroenterol. Hepatol.* **2020**, *5*, 533–534. [CrossRef]
22. Medema, G.; Heijnen, L.; Elsinga, G.; Italiaander, R.; Brouwer, A. Presence of SARS-coronavirus-2 RNA in sewage and correlation with reported COVID-19 prevalence in the early stage of the epidemic in the Netherlands. *Environ. Sci. Technol. Lett.* **2020**, *7*, 511–516. [CrossRef]
23. Randazzo, W.; Truchado, P.; Cuevas-Ferrando, E.; Simón, P.; Allende, A.; Sánchez, G. SARS-CoV-2 RNA in wastewater anticipated COVID-19 occurrence in a low prevalence area. *Water Res.* **2020**, *181*, 115942. [CrossRef] [PubMed]
24. Rimoldi, S.G.; Stefani, F.; Gigantiello, A.; Polesello, S.; Comandatore, F.; Mileto, D.; Maresca, M.; Longobardi, C.; Mancon, A.; Romeri, F.; et al. Presence and infectivity of SARS-CoV-2 virus in wastewaters and rivers. *Sci. Total Environ.* **2020**, *744*, 140911. [CrossRef] [PubMed]
25. Galloway, T.S.; Cole, M.; Lewis, C. Interactions of microplastic debris throughout the marine ecosystem. *Nat. Ecol. Evol.* **2017**, *1*, 116. [CrossRef] [PubMed]
26. Zettler, E.R.; Mincer, T.J.; Amaral-Zettler, L.A. Life in the "Plastisphere": Microbial communities on plastic marine debris. *Environ. Sci. Technol.* **2013**, *47*, 7137–7146. [CrossRef]
27. Debeljak, P.; Pinto, M.; Proietti, M.; Reisser, J.; Ferrari, F.F.; Abbas, B.; van Loosdrecht, M.C.M.; Slat, B.; Herndl, G.J. Extracting DNA from ocean microplastics: A method comparison study. *Anal. Methods* **2017**, *9*, 1521–1526. [CrossRef]
28. Oberbeckmann, S.; Löder, M.G.; Labrenz, M. Marine microplastic-associated biofilms—A review. *Environ. Chem.* **2015**, *12*, 551–562. [CrossRef]
29. Kirstein, I.V.; Kirmizi, S.; Wichels, A.; Garin-Fernandez, A.; Erler, R.; Löder, M.; Gerdts, G. Dangerous hitchhikers? Evidence for potentially pathogenic *Vibrio* spp. on microplastic particles. *Mar. Environ. Res.* **2016**, *120*, 1–8. [CrossRef]
30. Harrison, J.P.; Schratzberger, M.; Sapp, M.; Osborn, A.M. Rapid bacterial colonization of low-density polyethylene microplastics in coastal sediment microcosms. *BMC Microbiol.* **2014**, *14*, 232. [CrossRef] [PubMed]
31. McCormick, A.; Hoellein, T.J.; Mason, S.A.; Schluep, J.; Kelly, J. Microplastic is an Abundant and Distinct Microbial Habitat in an Urban River. *Environ. Sci. Technol.* **2014**, *48*, 11863–11871. [CrossRef]
32. De Tender, C.A.; Devriese, L.I.; Haegeman, A.; Maes, S.; Ruttink, T.; Dawyndt, P. Bacterial Community Profiling of Plastic Litter in the Belgian Part of the North Sea. *Environ. Sci. Technol.* **2015**, *49*, 9629–9638. [CrossRef]
33. Rochman, C.M.; Brookson, C.; Bikker, J.; Djuric, N.; Earn, A.; Bucci, K.; Athey, S.; Huntington, A.; McIlwraith, H.; Munno, K.; et al. Rethinking microplastics as a diverse contaminant suite. *Environ. Toxicol. Chem.* **2019**, *38*, 703–711. [CrossRef] [PubMed]
34. Rochman, C.M.; Browne, M.A.; Halpern, B.S.; Hentschel, B.T.; Hoh, E.; Karapanagioti, H.K.; Rios-Mendoza, L.M.; Takada, H.; Teh, S.; Thompson, R.C. Classify plastic waste as hazardous. *Nature* **2013**, *494*, 169–171. [CrossRef]
35. Leslie, H.A.; Depledge, M.H. Where is the evidence that human exposure to microplastics is safe? *Environ. Int.* **2020**, *142*, 105807. [CrossRef] [PubMed]
36. Vethaak, A.D.; Leslie, H.A. Plastic debris is a human health issue. *Environ. Sci. Technol.* **2016**, *50*, 6825–6826. [CrossRef] [PubMed]
37. Eichler, S.E.; Hopperton, A.P.; Alava, J.J.; Pereira, A., Jr.; Ahmed, R.; Kozlakidis, Z.; Ilic, S.; Rodriguez-Palacios, A. A Citizen Science facemask experiment and educational modules to improve coronavirus safety in communities and schools. *Front. Med.* **2020**, *7*, 486. [CrossRef]
38. Quinete, N.; Hauser-Davis, R.A. Drinking water pollutants may affect the immune system: Concerns regarding COVID-19 health effects. *Environ. Sci. Pollut. Res.* **2021**, *28*, 1235–1246. [CrossRef]
39. Hobbs, E.C.; Reid, T.J. Animals and SARS-CoV-2: Species susceptibility and viral transmission in experimental and natural conditions, and the potential implications for community transmission. *Transbound. Emerg. Dis.* **2021**, *68*, 1850–1867. [CrossRef]
40. CDC. Water and COVID-19 FAQs. In *Information about Drinking Water, Treated Recreational Water, and Wastewater*; Centers for Disease Control and Prevention U.S.; Department of Health & Human Services: Atlanta, GA, USA, 2020. Available online: https://www.cdc.gov/coronavirus/2019-ncov/php/water.html (accessed on 10 November 2020).
41. Wurtzer, S.; Marechal, V.; Mouchel, J.M.; Maday, Y.; Teyssou, R.; Richard, E.; Almayrac, J.L.; Moulin, L. Evaluation of lockdown impact on SARS-CoV-2 dynamics through viral genome quantification in Paris wastewaters. *MedRxiv* **2020**. [CrossRef]
42. Wu, F.; Zhang, J.; Xiao, A.; Gu, X.; Lee, W.L.; Armas, F.; Kauffman, K.; Hanage, W.; Matus, M.; Ghaeli, N.; et al. SARS-CoV-2 titers in wastewater are higher than expected from clinically confirmed cases. *mSystems* **2020**, *5*, e00614–e00620. [CrossRef]
43. Guerrero-Latorre, L.; Ballesteros, I.; Villacrés-Granda, I.; Granda, M.G.; Freire-Paspuel, B.; Ríos-Touma, B. SARS-CoV-2 in river water: Implications in low sanitation countries. *Sci. Total Environ.* **2020**, *743*, 140832. [CrossRef]
44. Gies, E.A.; LeNoble, J.L.; Noël, M.; Etemadifar, A.; Bishay, F.; Hall, E.R.; Ross, P.S. Retention of microplastics in a major secondary wastewater treatment plant in Vancouver, Canada. *Mar. Pollut. Bull.* **2018**, *133*, 553–561. [CrossRef] [PubMed]
45. Lambert, S.; Wagner, M. Microplastics are contaminants of emerging concern in freshwater environments: An overview. In *Freshwater Microplastics*; Wagner, M., Lambert, S., Eds.; Handbook of Environmental Chemistry 58; Springer: Berlin, Germany, 2018; pp. 1–23. [CrossRef]
46. Kershaw, P.J.; Rochman, C.M. *Sources, Fate and Effects of Microplastics in the Marine Environment: Part 2 of A Global Assessment*; IMO/FAO/UNESCOIOC/UNIDO/WMO/IAEA/UN/UNEP/UNDP Joint Group of Experts on the Scientific Aspects of Marine Environmental Protection (GESAMP): Rome, Italy, 2016.
47. Lebreton, L.C.; Van Der Zwet, J.; Damsteeg, J.W.; Slat, B.; Andrady, A.; Reisser, J. River plastic emissions to the world's oceans. *Nat. Commun.* **2017**, *8*, 15611. [CrossRef] [PubMed]

48. Onyena, A.P.; Aniche, D.C.; Ogbolu, B.O.; Rakib, M.R.J.; Uddin, J.; Walker, T.R. Governance Strategies for Mitigating Microplastic Pollution in the Marine Environment: A Review. *Microplastics* **2022**, *1*, 15–46. [CrossRef]
49. UNEP. Single-Use Plastics: A Roadmap for Sustainability. In *United Nations Environment Programme*; UNEP: Nairobi, Kenya, 2018; p. 90. Available online: https://www.unenvironment.org/resources/report/single-use-plastics-roadmap-sustainability (accessed on 27 October 2020).
50. Gibb, B.C. Plastics are forever. *Nat. Chem.* **2019**, *11*, 394–395. [CrossRef] [PubMed]
51. Sheth, M.U.; Kwartler, S.K.; Schmaltz, E.R.; Hoskinson, S.M.; Martz, E.J.; Dunphy-Daly, M.M.; Schultz, T.F.; Read, A.J.; Eward, W.C.; Somarelli, J.A. Bioengineering a Future Free of Marine Plastic Waste. *Front. Mar. Sci.* **2019**, *6*, 624. [CrossRef]
52. Pettipas, S.; Bernier, M.; Walker, T.R. A Canadian policy framework to mitigate plastic marine pollution. *Mar. Policy* **2016**, *68*, 117–122. [CrossRef]
53. Davis, K.E.; Beaty, F.; Sánchez, C. A flexible risk assessment framework for marine plastic pollution that synthesizes waste management and ecological impact data. *Mar. Policy* **2021**, *in press*. [CrossRef]
54. Cowan, E.; Booth, A.M.; Misund, A.; Klun, K.; Rotter, A.; Tiller, R. Single-Use Plastic Bans: Exploring Stakeholder Perspectives on Best Practices for Reducing Plastic Pollution. *Environments* **2021**, *8*, 81. [CrossRef]
55. Simon, N.; Raubenheimer, K.; Urho, N.; Unger, S.; Azoulay, D.; Farrelly, T.; Sousa, J.; van Asselt, H.; Carlini, G.; Sekomo, C.; et al. A binding global agreement to address the life cycle of plastics. *Science* **2021**, *373*, 43–47. [CrossRef]