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The COVID-19 pandemic and its implications on the environment

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A B S T R A C T

The emerging threat posed by COVID-19 pandemic has strongly modified our lifestyle, making urgent to reconsider the humans-environment relationships and stimulating towards more sustainable choices in our daily behavior. Scientific evidences showed that the onset of new viral pathogens with a high epidemic-pandemic potential is often the result of complex interactions between animals, humans and environment. In this context, the interest of the scientific community has also been attracted towards the potential interactions of SARS-CoV-2 with environmental compartments. Many issues, ranging from the epidemiology and persistence of SARS-CoV-2 in water bodies to the potential implications of lockdown measures on environmental quality status are here reviewed, with a special reference to marine ecosystems. Due to current sanitary emergence, the relevance of pilot studies regarding the interactions between SARS-CoV-2 spread and the direct and indirect environmental impacts of the COVID-19 pandemic, that are still a matter of scientific debate, is underlined.

1. Introduction

The current COVID-19 (Coronavirus Disease-19) pandemic is having an enormous impact on human health in terms of morbidity and mortality attracting the interest of the scientific community worldwide. Because of its rapid and global diffusion, the World Health Organization (WHO) declared the state of pandemic on March 11, 2020, inducing several countries worldwide to adopt specific restriction measures until full lockdown of human activities. This has caused, in turn, a global containment without precedents with severe impacts on all anthropic and economic performance, i.e. in touristic and food and agricultural sector (Cucinotta and Vanelli, 2020; WHO, 2020; Ma et al., 2021).

The pandemic has started from China where, in December 2019, clusters of human fatal pneumonia cases of unknown origin, but with clinical symptoms impressively resembling to the SARS-CoV syndrome, occurred in Wuhan, in the province of Hubei (Huang et al., 2020; Lai et al., 2020; Wang et al., 2020). From China, the virus has spread worldwide becoming pandemic and causing a large number of infections and deaths. To date, the virus is present in more than 200 countries, and at June 15, 2021 over 176.1 million cases and 3.8 million deaths have been reported globally since the start of the pandemic (WHO, 2021). However, these numbers are probably to be much higher, as they do not include positive asymptomatic or patients with poor symptoms (Pan et al., 2020). Especially the United States of America and the European countries are paying the highest count in terms of morbidity and mortality (Ceylan, 2020; Stokes et al., 2020; Tuite et al., 2020). In Italy, to June 15, 2021, 4,245,779 confirmed cases have been recorded from the beginning of the pandemic, with 127,038 deaths on a total of 68,896,197 performed swabs. These values make Italy the eighth country for total number of cases and of deaths globally (WHO, 2021). However, also thanks to the remarkable increase of performed vaccinations, these numbers is decreasing in all the national territory with a significant reduction of the pressure on the hospitals (Ministero della Salute, 2021).

The etiological agent of COVID-19 pandemic is the Severe Acute Respiratory Syndrome Coronavirus 2 (SARS-CoV-2), a new member of a family of viruses known as Coronaviruses (CoVs), recognized as responsible for high-risks pathological respiratory diseases (Burki, 2020). CoVs are RNA-viruses belonging to the Order Nidovirales, family Coronaviridae, capable of infecting a number of both terrestrial and aquatic organisms. To the family Coronaviridae belongs the sub-family Orthocoronavirinae, in turn divided into four genera: Alphacoronavirus, Betacoronavirus, Gammacoronavirus and Deltacoronavirus (Bukhari et al., 2018; de Groot et al., 2012; Malik et al., 2020). CoVs infect the gastrointestinal and respiratory epithelial cells of several organisms causing gastroenteritis and respiratory infections respectively (de Groot et al., 2012). Structurally, the viral particle consists of three different components: the genetic material (a RNA strand sized between...
2. Influence of environmental variables on the COVID-19 epidemiology and severity

The onset of new viral pathogens with a high epidemic-pandemic potential is often the result of complex interactions between animals, humans and environment (Coker et al., 2011). The latter can play an important role in the dynamics of human diseases since it has long been known that climate changes affect human health concerning not only chronic pathologies but also infectious diseases (Epstein, 1999, 2001, 2004; Kovats et al., 2000; Costello et al., 2009; Altizer et al., 2013; Bouzid et al., 2014; Willcox et al., 2015). Favorable climate conditions are necessary for survival, reproduction, transmission and spread of pathogens, of their vectors and hosts. Significant correlations between some climate indicators and the spread of COVID-19 epidemic have been documented (Araújo and Naimi, 2020; Ariola and Sghaier, 2020; Barceló, 2020b; Bashir et al., 2020). Indeed, changes in climate conditions can indirectly influence the epidemiology of infectious diseases through the modification of the living environment of the involved etiological agents (Epstein, 2001, Wu et al., 2014). According to the European Environment Agency (EEA, 2008), in the 20th century the global average surface temperature has increased by 0.74 °C, determining the reduction of the polar caps by 2.7% per decade and the increase of the global sea level of 1.8 mm per year since 1961. These changes have caused the occurrence of extreme weather events in many parts of the world. At the beginning of 2000s, the Intergovernmental Panel on Climate Change (IPCC) estimated an average temperature increase of 1.5–5.8 °C during the 21st century, with more and more frequent extreme events such as heat waves, floods and droughts (IPCC, 2001).

Several studies have shown that long-term climate warming can favor the geographic spread of many infectious diseases (Epstein et al., 1998; Rodó et al., 2013; Ostfeld and Brunner, 2015). Moreover, extreme weather events may influence the epidemiology of infectious diseases determining changes of their spatial and temporal distribution as well as of the intensity of outbreaks and of the global emergency and re-emergency of infectious agents (McMichael et al., 1996; Epstein, 2000; Kuhn et al., 2005; Wu et al., 2014). Many of the most common infectious diseases, and especially those insect-borne, are highly dependent on climate changes (Kuhn et al., 2005; Tian et al., 2015).

The role of environmental pollution in the spread and severity of the COVID-19 pandemic has also been evaluated. Atmospheric particulate matter (PM) could act as a carrier for many viruses. Indeed, PM may have increased the effectiveness of the SARS-CoV-2 spread via the aerosol creating a microenvironment suitable for its persistence. PM, especially particles smaller than 2.5 μm (PM2.5), and the associated microorganisms can be inhaled and reach the deep lung, and this allows the virus to multiply within the respiratory tract and to cause infection (Comunian et al., 2020).

Many studies reported a respiratory damage (acute respiratory inflammation, asthma attack, and death from cardio-respiratory diseases) following a prolonged exposure to air pollution (WHO 2016). Fine and ultrafine PM (PM 2.5 and PM 0.1) are now considered as one of the most important environmental risk factors, since they have been estimated to cause several million deaths per year worldwide (Lelieveld et al., 2015, 2019). Atmospheric pollutants can induce pro-inflammation and oxidation mechanisms in lungs and other organs, impairing also immune processes. From these evidences, a negative effect of air pollution on the prognosis of patients affected by COVID-19 is conceivable. A similar link between pollution and severe course of COVID-19 has been studied during the previous SARS epidemic. In Cui et al., 2003, observed that patients living in regions with moderated air pollution levels died more frequently compared to those living in regions with low air pollution levels. Air pollutants can elicit different toxicological mechanisms, such as cytotoxicity through oxidative stress with overproduction of Reactive Oxygen Species (ROS), DNA oxidative damage, mutagenicity, mitochondrial dysfunction and stimulation of pro-inflammatory responses (Di Pietro et al. 2009, 2011, 2011; Visalli...
et al., 2015). Moreover, in Italy, during the initial phases of COVID pandemic, remarkable higher mortality rates were observed in northern regions, notoriously more polluted compared to other ones, suggesting a role of pollution in the spread of pandemic (Conticini et al., 2020). However, current data on COVID-19 spread and mortality could be altered by the different approaches used for studying COVID-19-related deaths and infected people. Recent outbreaks of COVID-19 in countries such as Spain, France, USA and UK having pollution levels very different from those of the northern Italy suggest that in the spread and mortality of COVID-19 are probably involved different variables, among which the age and density of the affected population, its social habits, the policies adopted to contain the diffusion of the infection, and also meteorological conditions (Contini and Costabile, 2020).

Like other respiratory viruses, SARS-CoV-2 transmission, depending on the aerial spread of respiratory droplets, exposes the virus to external environmental conditions. Therefore, the spread of this virus is likely constrained by climate factors. Regarding the potential impact of latitude on the viral transmission, while some authors (Oktorie and Berd, 2020) have suggested as an unlikely event the spread of COVID-19 pandemics at high latitudes or poles, due to their characteristics of remote regions and with low population densities, a growing concern for the transmission to Antarctic wildlife has been reported by other studies (Barbosa et al., 2021). This aspect could be in relation to the increasing anthropogenic activities in these vulnerable regions of the Earth, stressing the need for suitable containment measures.

In this scenario, the outbreak of Coronavirus has been considered as a clear message sent by Gaia to humans to rethink our relationship with the environment and our wicked management of the living resources (Cazzola Gatti, 2020).

3. Impact of COVID-19 pandemic on the environment and biota

While the COVID 19 pandemic with the following worldwide lockdowns has had and continues to have a huge negative impact on the global economy, the environment has benefits in terms of pollution thanks to the stop of that activities, such as industries, transports and tourism, impacting so heavily on environmental quality (Bao and Zhang, 2020; Mahato et al., 2020; Raffaelli et al., 2020; Ray et al., 2020; Rodrigue-Urrego and Rodriguez-Urrego, 2020; Sharma et al., 2020) (Fig. 1). All the environmental compartments have benefited of the restrictive measures adopted to contain the infection (Siddique et al., 2021).

The reduction of pollution levels could support the nature to renovate herself and allows people to breathe a cleaner air than before. In China, following industrial shutdown and temporary stop in air emissions, Nitrogen Dioxide (NO₂) and carbon emissions have been reduced by 30% and 25%, respectively, and similar effects have been reported worldwide (Mahon, 2020; Myllyvirta, 2020). Many studies have been carried out in India to evaluate the impact of lockdown on air quality in this highly polluted country. Specifically, in the week 20–27 March 2020, the average PM 2.5 level in the capital, New Delhi, has decreased by 71%, ranging from 91 μg/m³ to 26 μg/m³ respectively (CPCB, 2020; Mate et al., 2020; Mitra et al., 2020). Over the same period, NO₂ level has been reduced by 71%, decreasing from 52 μg/m³ to 15 μg/m³. Similar decreases have been recorded in other Indian cities such as Bangalore, Chennai, Kolkata, and Mumbai (CPCB, 2020; Sharma et al., 2020). Cadotte (2020) reported decreasing air pollutants levels in the biggest cities of the world. In the South Korean capital Seoul, PM2.5 level has been reduced by 54% during the lockdown compared to the same period of the previous year, while in Wuhan (China) the air quality has improved by 44%. Also in Northern Italy, the severe restrictions on people movements following the partial lockdown and the subsequent total lockdown have determined a significant decrease of pollutants (PM10, PM2.5, benzene, CO, and NOx), mainly due to the stop of vehicular traffic (Collivignarelli et al., 2020).

The hydrosphere, including lakes, rivers, oceans, and groundwater

![Fig. 1. Positive and negative impacts on the environment of COVID-19 pandemic](image-url)
environments, has long been suffering from severe pollution because of rapid urbanization, industrialization, and overexploitation. During the lockdown, the major polluting human activities affecting aquatic ecosystems, among which industrial wastewater disposal, crude oil, heavy metals, and plastics (Hader, 2020), have drastically dropped or completely blocked. Therefore, the level of pollution has shrunk considerably. For example, in India, the highly polluted river Ganges, turned cleaner at several places during the lockdown (Mani, 2020). Positive effects with reduction of pollution determined by restrictive measures occurred also on marine and coastal environment (Canning-Clode et al., 2020) as well as on soil pollution (SanJuan-Reyes et al., 2021).

The lockdown has had positive effects also on several other environmental aspects such as the quality of beaches (Zambrano-Monserrate et al., 2020) and the remarkable reduction of noise pollution due to the stop of transport and industry, that are the major sources of noise (Auzan and Staboulli, 2020; Asensio et al., 2020; Bar, 2020). Even animal life benefits from the stop of the human activities. The behavioral changes of wild animals such as birds, insects, and street animals indicate the impact that human activities have on living beings. A certain correlation between atmospheric changes and changes in the behavior of animals during lockdown period has also been observed (Bar, 2020).

On the other hand, another important feature of COVID-19 pandemic is related to the massive use of disinfectants to counteract the viral transmission. Among these compounds, an extensive analysis of the potential impact on water quality and ecosystem health by the use of chlorine (NaClO) as the cheapest tool to avoid viral transmission, has been reported by García-Avila et al. (2020). These Authors have underlined that in the environment chlorine is transformed into highly dangerous compounds (i.e. halogenated organic compounds) that are toxic for marine biota, since they can persist in the environment longer than chlorine. Ecotoxicological effects related to the use of disinfectants have been reviewed by SanJuan-Reyes et al. (2021). Increased concern has also been posed by the amplified plastic pollution consequent to the use of Personal Protective Equipment (PPEs) such as protective masks or gloves (Abbasi et al., 2020), that have stimulated the search for sustainable alternatives (i.e. bio-based plastics, Patricio-Silva et al., 2020, 2021) or recycling practices related to circular economy approaches (Adyel, 2020). Indeed, COVID-19 pandemic has opened new point of views regarding the management of plastic wastes (Prata et al., 2020; De-la-Torre et al., 2021; SanJuan-Reyes et al., 2021), also in relation to their role as vectors of contaminants, including absorbed antibiotics that can select antibiotic-resistant and biofilm-producing bacterial strains (Lagana et al., 2018, 2019; Caruso, 2019; Patricio-Silva et al., 2021).

All the considerations related to the direct and indirect impacts of the COVID-19 pandemic on the aquatic environment stress the need for further studies, addressing the behavior of SARS-CoV-2 in aquatic systems while concerted efforts are needed to reduce the load of plastic wastes, in order to meet the Sustainable Development Goals (SDG), such as SDG 14 (United Nations, 2015).

A synthesis of current literature about the interaction of SARS-CoV-2 with the main environmental compartments (atmosphere, hydrosphere, lithosphere and biosphere) is shown in Table 1. Per each compartment, references have been assigned to a group according to the following criteria: 1) viral detection, transmission and persistence; 2) possible causes of viral spreading; 3) potential consequences of COVID-19 pandemic. From the table, it is clear that there is a strong link between air quality and COVID-19 infection in both the directions. Air pollution, especially that from Particulate Matter (PM) (Ali et al., 2021a) but also from microplastics (MPs) would favor the infection while the atmospheric conditions are important in transmission or dilution of the viral particles. However, there are many evidences showing that COVID-19 government restrictions reduced urban air pollution

### Table 1

| Compartment | Main issues/subjects | Grouping criteria |
|-------------|----------------------|------------------|
| **Atmosphere** | | |
| Barcelo, (2020b) | Air quality as a key environmental factor on the COVID-19 infections. | 2 |
| Bhaganagar and Bhimireddy, 2020 | Airborne transmission of COVID-19. Atmospheric stability and wind direction can affect transmission or dilution of the viral loading. | 1, 2 |

(continued on next page)
| Table 1 (continued) | Table 1 (continued) |
|---------------------|---------------------|
| **Water**           | Detection of important viral loads of SARS-CoV-2 from urban streams. |
| Cabill and Morris, 2020 | The loads found suggest that cases are probably a lot higher than the official data. Implications for disinfection of SARS-CoV-2 in low sanitation countries by polluted waters should be considered. |
| Carducci et al., 2020 | Kumar et al., 2020 | Not only the surface water, but also groundwater, represent SARS-CoV-2 control points through possible leaching and infiltrations of effluents from health care facilities, sewage, and drainage water. |
| Guerrero-Latorre et al., 2020 | Langone et al., 2021 | Risk of faecal-oral transmission of SARS-CoV-2 in water. |

| **Hydrosphere**     | **Wastewater**     |
|---------------------|---------------------|
| Low risk of contracting the SARS-CoV-2 virus via water sources, including wastewate and recreational waterbodies. | Wastewater monitoring has great potential to provide early warning signs on how broadly SARS-CoV-2 is circulating in the community, especially in those individuals showing mild symptoms or no symptoms at all. |
| Evidence of SARS-CoV-2 faecal excretion and increased concern about possible secondary transmission via water. Coronavirus excreted in faeces could reach wastewater treatment plants in an infective state, especially in cool climates. | Ahmed et al., 2020 | High incidence of SARS-CoV-2 and other viruses in American waterbodies. |

| **A. Facciol**      | **Guerrero-Latorre et al., 2020** |
|---------------------|---------------------|
| Evidence that COVID-19 government restrictions in response to COVID-19 reduced urban air pollution determining consistent declines in five of six major air pollutants. | | |
The SARS-CoV-2 virus may exist in wastewater discharge. The presence of coronaviruses in wastewater can result in the discharge of viral material to wastewater systems. Wastewater may pose a risk to environmental and public health. Therefore, there is also the question of how long coronavirus can survive and remain contagious after wastewater discharge.

Wartecki and Rzymski, 2020

Table 1 (continued)

| Author(s) | Year | Description |
|-----------|------|-------------|
| Bilal et al., 2020 | | The SARS-CoV-2 virus may exist in wastewater, but it must be recognized and concentrated. Therefore, there is also the question of how long coronavirus can survive and remain contagious after wastewater discharge. |
| Daughton, 2020 | | Wastewater-based epidemiology (WBE) could play critical roles in the Covid-19 pandemic and can help solve the pressing problem of insufficient clinical diagnostic testing. |
| Haramoto et al., 2020 | | SARS-CoV-2 RNA was detected in wastewater in Italy for the first time. Wastewater-based epidemiology can be applied for COVID-19 surveillance. |
| Anand et al., 2021 | | SARS-CoV-2 can be found in soil (i.e. up to 550 copies/L). None of influent and river water samples tested positive for SARS-CoV-2 RNA. SARS-CoV-2 RNA was detected in wastewater when the reported cases in the community were high. |
| Godoy et al., 2021 | | Aquatic food does not present the risk of secondary transmission via water. The excreted virus could constitute a significant reservoir for coronavirus infections of different genera, but this requires surveillance in wild animals. |
| Barbosa et al., 2021 | | Among Antarctic wildlife in silico analyses suggested that cetaceans are at greater risk of infection whereas seals and birds appear to be at a low infection risk. |
| Nabi and Khan, 2020 | | The Angiotensin-converting enzyme 2 (ACE-2), a receptor for SARS-CoV-2 binding found in aquatic mammals can increase the vulnerability to SARS-CoV-2 infection. SARS-CoV-2 can possibly cause infection in marine mammals. |

Table 1 (continued)

| Author(s) | Year | Description |
|-----------|------|-------------|
| | | Wastewater can be a source of SARS-CoV-2 to soil. Municipal waste from people infected with SARS-CoV-2 or people in contact with patients with COVID-19 may be a hazard. |
| | | Landfilling of municipal solid waste has increased by 34.7% after the outbreak of COVID-19. Secondary contagion from improper management of municipal solid waste is probable. |
| | | Aquatic ecosystems, particularly in areas with poor sanitation. This may potentially increase the risk of infection for individuals involved in sewage management. |

Determine consistent declines. Moreover, there is a large evidence of SARS-CoV-2 elimination via faeces with increased worries about possible secondary transmission via water. The excreted virus could reach wastewater treatment plants in an infective state. However, it has been reported a frequent rapid inactivation of SARS-CoV-2 in water systems and that there is no current evidence that SARS-CoV-2 is transmitted through contaminated drinking-water. Detection of important viral loads of SARS-CoV-2 from urban SARS-CoV-2 is widely reported and this presence can be used to monitor COVID-19 in a community. In addition, SARS-CoV-2 can be found in soil even follow
the spill of sewage that can act as a source and evidences reported a survival of enveloped viruses in this compartment up to 90 days. However, no paper has been published up to date indicating how this virus could be quantified in soil samples.

Finally, in Table 2 are reported studies about the environmental impact of the use of Personal Protective Equipment (PPE) during the COVID-19 pandemic. The evidences show that the COVID-19 pandemic has resulted in an exceptional increase of production, consumption, and disposal of PPE, especially surgical face masks. The overuse of PPEs is determining the increase of plastic pollution especially in water environments. Plastic waste in freshwater and marine environment can be easily ingested by higher organisms, such as fishes, entering in the food chain and potentially determining chronic health problems to humans.

4. Environmental survival of SARS-CoV-2

Although the main and better-known route of transmission of CoVs is the direct one through the emission of droplets (Chen et al., 2020), the environmental survival of SARS-CoV-2 outside the human body and its potential environmental spread via different matrices such as water, air, and food should not be ignored (Núñez-Delgado, 2020). Recently, Yeoh et al. (2020) highlighted the potential fecal-oral transmission of SARS-CoV-2. Indeed, the release through faeces has been confirmed for SARS-CoV (Wang et al., 2005a; Petricch et al., 2006), MERS-CoV (Zhou and Zhao, 2017) and SARS-CoV-2 (Tian et al., 2020; Zhang et al., 2020b). Moreover, some researchers focused their attention on the possible CoVs transmission through bioaerosols originated from toilet flushing, as demonstrated by Yu et al. (2004) for SARS-CoV and recently suggested by Ong et al. (2020) for SARS-CoV-2. Finally, an involvement of contaminated food in CoVs transmission can be supposed given the already established survival of the human or animal CoVs on vegetables (Mullis et al., 2013; Yépez-Gómez et al., 2013).

The fate of the SARS-CoV-2 in the urban water cycle has raised a great concern in the scientific community, also regarding the pathways of transmission of COVID-19 via building sanitary plumbing systems (Bilal et al., 2020). The need for adequate monitoring programs to evaluate wastewater treatment and fate of urban waters has been underlined, in the light that viral survival and persistence in water systems after wastewater discharge depend on several factors (i.e. temperature, UV or solar inactivation, organic substances, potential competitor microorganisms). The migration pathways of SARS-CoV-2 in the aquatic environments have been reviewed by Kumar et al. (2020). Since most the majority of fecal-oral transmitted viruses are highly persistent in the aquatic environment, the Authors underline that knowledge on SARS-CoV-2 persistence in water is essential to follow viral fate in water, wastewater and groundwater and subsequent human exposure. Therefore, surface water and groundwater represent relevant viral control points through possible leaching and infiltrations of effluents from health care facilities, sewage, and drainage water. In aquatic environments, a literature review on the occurrence, persistence and possible management of SARS-CoV-2 has been reported by Patel et al. (2021), who have analyzed the main questions related to these issues and suggested the suitability of wastewater-based epidemiology studies to detect the spread of the pandemic.

Several studies have been carried out to assess the presence and the persistence of the SARS-CoV-2 in sewage and wastewater, recognizing this environmental compartment as a potential way of exposure to infection (Ahmed et al., 2020; Barceló, 2020a, b; Corpuz et al., 2020; Lodder and de Roda Husman, 2020; Nemudryi et al., 2020; Reusken et al., 2020). Cahill and Morris (2020) have explored the potential risks related to the use of recreational waters, concluding that there have been no reports of humans contracting the SARS-CoV-2 via faecal-oral transmission to date and therefore the risk of SARS-CoV-2 exposure to recreational water users is believed to be low, although the potential risk of faecal-oral transmission cannot be excluded where SARS-CoV-2 is present in its infectious state following excretion from human body. At

### Table 2

| References | Plastic materials | Main issues/subjects |
|------------|-------------------|---------------------|
| Ammendolia et al., (2021) | PPEs (disposable gloves, face masks and disinfecting wipes) | The COVID-19 pandemic has resulted in an unprecedented surge of production, consumption, and disposal of personal protective equipment (PPE). In this study, a total of 1306 PPE debris items were documented, with the majority being disposable gloves (44%), followed by face masks (31%), and disinfecting wipes (25%). |
| Aragav, (2020) | Surgical face masks | Face masks are easily ingested by higher organisms, such as fishes, and microorganisms in the aquatic life which will affect the food chain and finally chronic health problems to humans. |
| Arduoso et al., (2021) | PPEs (face masks, gloves, face protector, protective suits, safety shoes) | The lack of preparation of appropriate protocols, poor handling of increased volumes of medical waste and deficiencies in the management of medical and domestic waste collection services could increase in the medium/long term the levels of plastic pollution on beaches, coasts and rivers in South America. |
| Cordova et al., (2021) | PPEs (medical masks, gloves, hazard suits, face shields, raincoats) | Study on riverine debris releases into Jakarta Bay, Indonesia, during COVID-19 pandemic showing an unprecedented presence of PPE (medical masks, gloves, hazard suits, face shields, raincoats) that accounted for 15–16% of the collected river debris daily. |
| De la Torre et al., 2021 | PPEs (face masks, face shields, and gloves) | The overuse of PPEs during the COVID-19 pandemic is worsening plastic pollution in the marine environment. |
| Fadare and Okofo, (2020) | Face masks | Plastic and plastic particle waste are getting into waterways from where they reach the freshwater and marine environment adding to the presence of plastics in the aquatic medium. |
| Panesar and Hait, (2021) | PPEs (goggles, face masks, gowns, gloves and hand sanitizers), plastic bottles/caps, packaging material, garbage bags | Plastics have been deemed as evil polluter due to their indiscriminate littering and mismanagement amid increased plastic usage and waste generation during this unprecedented crisis. |
| Pereira de Albuquerque et al., 2021 | Face masks | The presence of face masks in Organic Fraction of Municipal Solid Waste (OFMSW) could negatively affect methane productivity and kinetics. Face masks can be a potential source of plastic and microplastics pollution and amplify the transmission of antibiotic resistance genes to the ecosystem. |
| Prata et al., (2020) | PPEs (face masks, surgical gowns and gloves) | Mismanagement of personal protective equipment (PPE) during the COVID-19 pandemic is resulting in widespread environmental contamination. This poses a risk to public health (continued on next page) |
this regard, the risks of SARS-CoV-2 infection posed by faecal contaminated water have been assessed by Shuter et al. (2020), who have reported viral stability within water up to 25 days, and that rivers, waterways and water systems contaminated by high infection rates can provide infectious doses > 100 viral copies per 100 ml of water. This issue is mainly related to the evidence that other viruses with the same structural characteristics, such as H1N1 “Spanish flu”, avian influenza H5N1 and H7N9, SARS-CoV, and MERS-CoV, have been detected in sewage holding tanks of an international ferry boat, as well as on surface of air-conditioners and vents on busy public transport systems, the presence of SARS-CoV-2 was detected (Mouchtouri et al., 2021). In this regard, Wang et al. (2005b) showed that SARS-CoV can persist in stools and serum up to 96 h. Also in sewage holding tanks of an international ferry boat, as well as on surface of air-conditioners and vents on busy public transport systems, the presence of SARS-CoV-2 was detected (Mouchtouri et al., 2020). Specifically, the Authors assumed the transfer of infected waste continuously endangering the environment.

Table 2 (continued)

| References                     | Plastic materials                        | Main issues/subjects                                                                 |
|--------------------------------|------------------------------------------|--------------------------------------------------------------------------------------|
| Rume and Islam,               | PPES (face mask, hand gloves, gowns, goggles, face shield) | as waste is a vector for SARS-CoV-2 virus, which survives up to 3 days on plastics, and there are also broad impacts to ecosystems and organisms. |
| (2020)                        |                                          | There are some negative consequences of COVID-19, such as increase of medical waste, haphazard use, disposal of disinfectants, mask, and gloves and burden of untreated wastes continuously endangering the environment. |
| Salihu et al., (2021)         | Face masks                               | A single surgical mask submitted to 180 h UV-light irradiation and vigorous stirring in artificial seawater may release up to 173,000 fibers/day. Moreover, microscopic analysis carried out onto surgical masks collected from Italian beaches highlighted the same morphological and chemical degradation observed in the masks subjected to the artificially weathering experiments, confirming the risks of a similar microfiber release into the marine environment. |
| Sangkhram, (2020)             | Face masks                               | In Asia, the number of face masks used and medical waste has increased with the steady increase in the number of confirmed SARS-CoV-2 cases. |
| Selvaranjan et al., (2021)    | Face masks                               | The number of face masks used during the COVID-19 pandemic increased worldwide. These additional enhanced face masks containing plastic contributed to micro-plastic pollution in the aquatic environment and also significantly impact the soil. |

5. Presence and survival of CoVs in marine environments and biota

Viruses are the most abundant particles in all the environments, including seas and oceans where they are present in a concentration of about 10-fold greater than prokaryotic (Suttle, 2005, 2007). Previous studies have highlighted that marine viruses play a critical role in determining aquatic communities and influencing ecosystem dynamics (Bergh et al., 1989; Proctor and Fuhrman, 1990; Suttle et al., 1990). In marine waters, viruses are present at a concentration ranging from about 10^7 to 10^10 L^-1, while in marine sediments from 10^7 to 10^16 g^-1 of dry weight. Many studies showed that viruses are abundant especially in surface water and subsurface sediments where their concentration exceeds by 10–1000 times that recorded along the water column (Paul et al., 1993; Maranger and Bird, 1996; Danovaro and Serresi, 2000; Danovaro and Serresi, 2002, 2008a, b). Some authors found a significant difference in viral abundance among different marine habitats. Specifically, the highest viral presence was found typically in low-salinity coastal waters (Colley and Welschmeyer, 2002; Corinaldesi et al., 2003; Clasen et al., 2008), and surface coastal sediments (Danovaro et al., 2008b), decreasing up to three orders of magnitude in deep waters and sea sediments (Hara et al., 1996; Magagnini et al., 2007; Danovaro et al., 2008a, b). Virioplankton abundances were also found to decrease moving from productive coastal zones to oligotrophic offshore surface waters (Wommack and Colwell, 2000; Corinaldesi et al., 2003; Payet and Suttle, 2008).

Many characteristics of waters, such as temperature, salinity, turbulence and nutrient availability, remarkably influence viral presence in marine ecosystems, because they affect the presence, distribution and metabolism of the planktonic cells acting as viral hosts (Wommack and Colwell, 2000; Weinbauer, 2004). This is supported by the previously documented significant positive correlation between the viral production and prokaryotic growth rate (Glud and Middelboe, 2004; Mei and Danovaro, 2004; Danovaro et al., 2008b).

As SARS-CoV-2 can reach the marine environment through human fecal emissions and, therefore, the human effluents, it is important to understand if and to what extent this transmission pathway can affect marine life. Wastewater monitoring studies aimed at detecting SARS-CoV-2 are currently carried out in order to better understand the viral epidemiology (Ahmed et al., 2020; Duah et al., 2020; Londer and de Roda Husman, 2020; Medema et al., 2020; Orive et al., 2020; Randazzo et al., 2020). The detection of SARS-CoV-2 in wastewater suggests that CoVs may be introduced into water bodies through urban or agricultural
runoff or via wastewater effluents. Indeed, very recently, reports have shown the presence of SARS-CoV-2 in rivers contaminated by untreated human sewage (Guerrero-Latorre et al., 2020; Haramoto et al., 2020; Rimoldi et al., 2020). Ye et al. (2016) showed that the coronavirus MHV (Murine Hepatitis Virus) in raw wastewater underwent a 90% reduction in its infectivity after 13 h at 25 °C, but remained longer infectious (36 h) at 10 °C. The collected evidences suggested that after excretion whole coronavirus particles probably may survive in wastewater depending on different environmental conditions, and, after discharge into aquatic habitats, they may reach coastal marine waters where, however, undergo considerable damage and loss of infectivity. Studies showed that in seawater different viruses, both of eukaryotes and phages, experience particle decay, at different rates, as a result of sunlight (UV-C radiation) and interaction with nucleases and proteases present in marine microorganisms and free in water (Heldal and Bratbak, 1991; Wommack et al., 1996; Noble and Fuhrman, 1997; Wilhelm et al., 1998). However, the decay of CoVs in natural waters has not been studied.

Concerning the presence of CoVs in biota, members of the family Coronaviridae are known to infect not only birds and mammals, but also invertebrates, reptiles, amphibians and even fish (Bukhari et al., 2018; Shi et al., 2018; Mordecai et al., 2019). Confirmed associations of CoVs with aquatic biota have been listed by Warteczi and Rymski (2020), who have suggested the role of aquatic environments inhabited by large populations of flock-feeding or colony-forming fishwafows and frequently visited by bats, as possible hotspots of CoVs, with potential cross-species transmission. Regarding marine biota, to date there is no evidence of Betacoronaviruses members hosted by marine animals, while members of both Alphacoronaviruses and Gammacoronaviruses have been described in marine mammals (Schütze, 2016; Bossart and Duignan, 2018) as such as Alphacoronavirus in the Harbor Seal (Bossart and Schwartz, 1990), Gammacoronavirus in the Pacific Harbor Seal (Nollens et al., 2010), Gammacoronavirus in the Beluga Whale (Mihindukulasuriya et al., 2008) and Gammacoronavirus in the Bottlenose Dolphin (Woo et al., 2014). However, it must be noted that although these viruses are associated with respiratory diseases in pinnipeds and cetaceans, they are poorly similar to SARS-CoV-2 because both Gammacoronaviruses and Alphacoronaviruses share little homology with the new CoV. Wild birds are known to be viral reservoirs, and birds living in marine environment are also known to harbor CoVs. For example, a novel coronavirus, member of the Gammacoronaviruses, was identified in American herrings and great black backed gulls (Canuti et al., 2019). Interestingly, these sea bird CoVs belong to the same clade of marine mammal CoVs, suggesting that a possible spillover between these animals has occurred. Marine Gammacoronaviruses have morphology, genome organization, and replication highly similar to human CoVs (Mihindukulasuriya et al., 2008; Woo et al., 2014). While no marine Gammacoronavirus has been cultivated, experiments using the avian Gammacoronavirus Infectious Bronchitis Virus (IBV) have shown that it shares with human CoVs similar entry, replication and shedding. Moreover, while it has been demonstrated that SARS-CoV-2 recognize the angiotsin converting enzyme 2 (ACE2) as its cellular receptor (Yan et al., 2020), IBV binds to sialic acid but, despite it infects primarily respiratory tissues, both they may have a wide cell tropism and can infect multiple sites (Winter et al., 2006; Promkuntod et al., 2014; Bande et al., 2016).

A recent review (Godoy et al., 2021) has focused on SARS-CoV-2 contamination and transmission via aquatic food animals or their products, highlighting that despite this virus is not a foodborne virus, it can survive on contaminated cold-chain food sources. Nevertheless, SARS-CoV-2 does not replicate in cold blood organisms who have a different ACE2 cell receptor and therefore it is unlikely that human consumption of aquatic animals or their products can transmit SARS-CoV-2, as well as that marine CoVs that are neither zoonotic nor closely related to human CoVs can cross the species barrier.

6. Conclusions

The COVID-19 pandemic is having an impressive impact on human society and activities forcing the world population to change its habits and behaviors. Climate changes with their impact on the environment and animals, have played surely a role in the emerging and spread of SARS-CoV-2. The spreading of the infection has pushed the governments to adopt restrictive measures in order to contain the number of infected people and deaths. However, such strategies have had a positive impact on the environment, reducing pollution and improving air and water quality. This matter should increase the awareness of the importance of the environment and environmental pollution. Some previous studies have been carried out to increase current public knowledge on this important issue (Gardacci et al., 2019).

The impact of SARS-CoV-2 on the environment and the involvement of others animal species have been reviewed in this study. The presence and persistence of this virus in the environment, especially in aquatic environments, have been the subject of several studies. However, from the currently available scientific evidences, it is possible to assume that due to the high decay rates and the high dilution rates, SARS-CoV-2 and CoVs in general are not able to persist in natural habitats for long time periods. This would minimize the risk of SARS-CoV-2 infection of any susceptible host that potentially could act as a viral reservoir. However, since terrestrial mammals and cetaceans have, similarly to humans, on ACE2 the receptor binding domains, surviving virions may potentially infect these animals especially near urban wastewater outfalls (Nabi and Khan, 2020).

In conclusion, CoVs as free persistent virions, especially in marine and freshwater ecosystems, are not frequent, but this could depend on the limited knowledge of the viral diversity in aquatic reservoirs (Mordecai and Hewson, 2020; La Rosa et al., 2020b). Current understanding of the potential risk represented by the spread of SARS-CoV-2 in marine environments can be improved by a much broader monitoring and analysis of the dynamics of viral spread through further studies on this issue.

Citizens around the world are making responsible efforts to reduce viral transmissions and preserve human health. The pandemic teaches us that the same commitment must be dedicated to protecting and preserving the health of the planet Earth. Choosing more sustainable actions for the planet represents the greatest challenge for the future of humanity. In this scenario, actions such as supporting the recovery and development of impacted communities, favoring the resilience of coastal ecosystems and safeguarding their services are strongly recommended (Steven et al., 2020; United Nations Environment Programme-Mediterranean Action Plan, 2020).

Authors’ contributions

PL and GC conceived the original idea. PL, GC and AF carried out the bibliographic research, wrote the article and elaborated tables and figure.

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