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Implications of COVID-19 pandemic on environmental compartments: Is plastic pollution a major issue?



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ABSTRACT

The COVID-19 anthropause has impacted human activities and behaviour, resulting in substantial environmental and ecological changes. It has assisted in restoring the ecological systems by improving, for instance, air and water quality and decreasing the anthropogenic pressure on wildlife and natural environments. Notwithstanding, such improvements recessed back, even to a greater extent, when considering increased medical waste, hazardous disinfectants and other chemical compounds, and plastic waste disposal or mismanagement.

This work critically reviews the short- and long-term implications of measures against COVID-19 spreading, namely on human activities and different environmental compartments. Furthermore, this paper highlights strategies towards environmental restoration, as the recovery of the lost environment during COVID-19 lockdown suggests that the environmental degradation caused by humans can be reversible. Thus, we can no longer delay concerted international actions to address biodiversity, sustainable development, and health emergencies to ensure environmental resilience and equitable recovery.

Introduction

COVID-19 pandemic became more than a health crisis, as it has been affecting all human societies and the environment. Since its outbreak in late December 2019, and as an attempt to reduce virus transmission, governments worldwide have imposed several restrictions on industrial activities, commerce, outdoor activities, movement of vehicles, goods, and people; resulting in dramatic reductions in human activity, production and distribution of goods and services, commonly referred as “anthropause” (Rutz et al., 2020). Alongside, COVID-19 triggered a significant change in public behaviour at different levels (e.g., health/environmental perception, use and consumption of goods) (Drury et al., 2020; Li et al., 2020a; Abbasi et al., 2020). Anthropause and changes in human behaviour have been providing an unprecedented mechanistic insight on how they can interfere with different aspects of the environmental compartments (Zambrano-Monserrate et al., 2020).

Several studies have been addressing the effects of the COVID-19 pandemic on the environment throughout the first year, although the

majority is focused on specific environmental compartments (e.g., air, water, soil, or biota) (see table 1 and references therein) or with a particular perspective (e.g., plastic pollution, chemical pollution, marine environment, virus epidemiology and persistence) (e.g., Ong et al., 2021; Loh et al., 2021; Facciola et al., 2021). Therefore, this paper provides an overview of the positive and negative effects of the COVID-19 pandemic measures and related human activities on the different environmental compartments, along with an integrative discussion on the major drivers and effects in the long term, with particular emphasis on plastic pollution. Furthermore, it highlights strategies towards environmental restoration and sustainability, as the recovery of the lost environment during COVID-19 lockdown suggests that the environmental degradation caused by humans can be reversible.

Positive effects of COVID-19 pandemic on the environment – a short-term reality

The first evidence on the impact of COVID-19 on the environment was, in fact, positive and mostly related to the global anthropause. With lockdown measures and reduced human activities (particularly in the industrial and transport sectors), the release of widely known air pollutants, such as sulphur dioxide (SO₂), nitrogen dioxide (NO₂), carbon

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Table 1

Summary of the positive and negative impacts of COVID-19 on environmental compartments.

Positive	Negative
Air compartment	
Improved outdoor air quality in the first trimester (Tobías et al., 2020; Bashir et al., 2020) Decreased pollution noise in Europe (ESA 2020) Decreased primary pollutants and volatile organic compounds (L. Li et al., 2020) Decreased concentration of the most harmful ultrafine particles for health (PM 2.5)[10] Reduced fossil-fuel consumption in the first trimester (Qarani, 2020) Decreased GHG emission (Ficetola and Rubolini, 2020; Wang and Su, 2020) Decreased dust storms (Qarani, 2020)	Decreased indoor air quality (Dutheil et al., 2020; Faridi et al., 2020) Back-to-normal air pollution from the second semester (Tollefson, 2021; Liu et al., 2020) Increased acoustic footprint (Ulloa et al., 2021) Increased emissions of GHG and hazardous chemical compounds in a long-term due to increased incineration activities worldwide (as reviewed by Hantoko et al. (Hantoko et al., 2021)) Delays on the 26th COP on the UN frameworks Convention on Climate Change (Ortiz et al., 2021)
Terrestrial compartment	
Decreased household food waste in the first trimester (Jribi et al., 2020) Reduced touristic reassurance on natural environments (Qarani, 2020) Decreased coal consumption in China (Rume and Islam, 2020) Decreased oil extraction, mining, quarry (Qarani, 2020) Cleaner beaches (Zambrano-Monserrate et al., 2020) Decreased on human-made fires (Poulter et al., 2021; Paudel, 2021; Rodrigues et al., 2020)	Increased landfilling (Zand and Heir, 2020) with potential long-term geomorphological implications and increased release of toxic leachates (Silva et al., 2021) Increased disinfection routines with hazardous chemical substances in outdoor environments (e.g., beaches) (Silva et al., 2021a) Potential delay on crop planting due to limited imports on fertilizers (Hanyabui et al., 2021) Prevalence of SARS-CoV-2 in soils (Anand et al., 2021) and sludge (Carrillo-Reyes et al., 2021) Potential increase on intensive cultivation of vulnerable areas due to the emphasis of local food production (lockdown pressure) (Poch et al., 2020) Increased plastic pollution related to the healthcare and packaging sector (Silva et al., 2021; Gorrasi et al., 2020)
Aquatic compartment	
Decreased Industrial and Commercial wastewater effluent release (Qarani, 2020) Improved surface water quality in the first trimester (Dutta et al., 2020) Cleaner waterways (Zambrano-Monserrate et al., 2020; Soto et al., 2021) Reduced ocean acidification was expected due to a decrease in CO ₂ (Ong et al., 2021) Reduced acoustic pollution (Thomson and Barclay, 2020; Barclay and Thomson, 2021)	Increased residential wastewater effluents release (Qarani, 2020) Increased floods (Qarani, 2020) Increased water demand (Kim et al., 2021) Increased plastic pollution (particularly PPE) (Silva et al., 2021b, 2021c) Detection of important viral loads of SARS-CoV-2 from urban streams (Guerrero-Latorre et al., 2020) Increased concentrations of pharmaceuticals and personal care products against COVID-19 in lakes, and WWTP-river-estuary system in China (Chen et al., 2021) Potential excess of chlorine disinfectants on aquatic systems (García-Ávila et al., 2020) Increased plastic pollution (particularly PPE) (Silva et al., 2021b; Gorrasi et al., 2020; De-la-Torre and Aragaw, 2020) Contribution of microfibres and hazardous chemical compounds released from disposable facemasks (Sullivan et al., 2021; Saliu et al., 2021)
Biological compartment	
Decrease deforestation (Chakraborty and Maity, 2020) Decreased wildlife trade (Chakraborty and Maity, 2020) Decreased wildlife-vehicle collision (Shilling et al., 2021) Decreased wildlife observation in South Africa (Rose et al., 2020) Decreased pressure on fish and other aquatic lives (Loh et al., 2021; Qarani, 2020) Decreased fire occurrence, with vegetation recovery (Qarani, 2020) Increased animal movements (Qarani, 2020; Lombrana, 2020; Child, 2020) Resurgence of endangered species (e.g., leatherback sea turtles, reef-fish) (Edward et al., 2021; Geggel, 2020)	Increase in aggressive, synanthropic predators (e.g., crows) in natural coastlines, altering animal assemblage structure (e.g., small mammals, reptiles, crustaceans) (Gilby et al., 2021) Wildlife interaction with PPE (ingestion, entanglement, amongst others) (Hiemstra et al., 2021) Increased in opportunistic species such as rodents (Bedoya-Pérez et al., 2020), with modulation of their behaviour (Manda, 2020) Increased susceptibility of wildlife (e.g., mammals) to virus (including SARS-CoV-2) infection (Barbosa et al., 2021), and COVID-19 pneumonia (Nabi and Khan, 2020) Higher ecotoxicological risk associated with antiviral drugs (e.g., favipiravir, lopinavir, umifenovir and ritonavir) and disinfectants (Kuroda et al., 2021; Zhang et al., 2020; da Luz et al., 2021; Mendonça-Gomes et al., 2021) Foodborne transmission of SARS-CoV-2 through animal products (Hu et al., 2021) Microfibres released from facemasks induced ecotoxicity on soil invertebrates (springtails and earthworms) (Kwak and An, 2021) Increased insecurity on food provisioning (e.g., travel limitations decreased assess to essential raw materials for farming activities) in the first semester (Senten et al., 2020; Swinnen and McDermott, 2020; Adelodun et al., 2021) Delays on the 15th conference of the parties (COP) of the UN Convention on Biological Diversity (Ortiz et al., 2021)

oxide (CO), ammonia (NH₃) and fine particulate matter (PM_{2.5}, PM₁₀), reduced substantially (30–60%) in highly populated cities (Li et al., 2020b; Rodríguez-Urrego and Rodríguez-Urrego, 2020; Barceló, 2020). For example, Delhi (India) reported a reduction in PM₁₀, PM 2.5, SO₂, NO₂, CO, and NH₃ concentrations by 52, 53, 18, 53, 30, and 12%, respectively, in March 2020 comparatively to the same months in 2019 (Bhat et al., 2021).

A similar trend was also observed in carbon dioxide (CO₂) emissions. For example, China dropped their CO₂ emission by 18.7% (182 Mt) compared to the first 2019's quarter, with a significant share (61.9%) related to the transport sector. A sudden drop in CO₂ emission (up to 40%) was also observed in several regions of Italy (Fattorini and Regoli, 2020), São Paulo (Brazil) (Freitas et al., 2020), Barcelona (Spain) (Tobías et al., 2020), and Kuala Lumpur (Malaysia) (Suhaimi et al., 2020). According to UK based climate science and policy website Carbon Brief, COVID-

19 anthropause could have cut 1600 t of CO₂, equivalent to 4% of the global total in 2019 (Evans 2020).

Another change is related to ozone recovery. During the lockdown period (March and April 2020), unprecedented healing of the ozone hole was observed, which is reported by Copernicus Atmosphere Monitoring Service (CAMS) (Lopez, 2021)

Watercourses also showed signs of recovery in the first stage of the pandemic. For example, 29 waterways in Malaysia (Goi, 2020), Ganga River (India) (Dutta et al., 2020), and Venice lagoon (Italy) (Braga et al., 2020) revealed a generalised improvement in their water quality indexes (i.e., turbidity). Such water quality improvement could be related to a decrease in water acidification due to the decline in atmospheric NO₂ and CO₂, which often ends up in the water compartments, through acid rain or surface absorption (Ong et al., 2021; Lükewille and Alewell, 2008); or through the decrease in hazardous

chemicals release, via industrial activities, tourism, and water-traffic (Dutta et al., 2020; Yunus et al., 2020). The reduction in water-traffic, fisheries, and tourism, also resulted in a decrease in water acoustic noise (Thomson and Barclay, 2020), allowing aquatic species that rely on eco-localization (e.g., cetaceans) to reclaim habitats (as reviewed by Ong et al., 2021; Loh et al., 2021).

The decrease in human activities related to strong environmental interference resulted in decreased wildlife-human interactions (collision, trade/predation, observation) (Chakraborty and Maity, 2020; Shilling et al., 2021; Rose et al., 2020). Some species increased their movements (Qarani, 2020), while others (endangered) seemed to resurge (Edward et al., 2021). Numerous wildlife animals ventured into the cities during the lockdown (e.g., deer's, wild pigs, amongst others) as reported by several media (e.g., (BBC, 2020). In addition, vegetation recovery was also observed, primarily due to ceasing deforestation activities and a decline of fire outbreaks (Chakraborty and Maity, 2020; Qarani, 2020). The number of human-induced active fires indeed declined during COVID-19 lockdown, as observed, for instance, in some U.S. states (Poulter et al., 2021), Nepal (Paudel, 2021), and some Southern-European countries (Rodrigues et al., 2020).

Negative effects of COVID-19 pandemic on the environment – an intimidating journey

As the economy is slowly re-established, the mode “business-as-usual” became a reality, revoking the positive environmental effects evidenced in the early stages of the pandemic. For example, despite the sharp drops early in the first semester (by June 2020), global emissions of CO₂ seemed to bounce back to average (pre-COVID-19) values in the second semester (by October 2020) (Tollefson, 2021; Liu et al., 2020). This is also predictable for air pollutants, such as SO₂, NO₂, and fine particulate matter (PM), with an aggravated scenario as such pollutants have the potential to threaten human and animal health by contributing to pathogen spreading and consequent higher infections (as reviewed by Facciola et al., 2021).

With the COVID-19 pandemic persistence, wastewater effluents ended up increasing substantially (Qarani, 2020), containing massive loads of disinfectants (Silva et al., 2021a), soaps, and detergents (Chirani et al., 2021) to reduce virus transmission, along with antimicrobials (Kumar et al., 2021) and antiviral drugs (Kuroda et al., 2021) to deal with the disease symptoms. For example, from the outbreak until 2020 March, the city of Wuhan (China) dispensed at least 2000 tons of disinfectants (Zhang et al., 2020). It is estimated that from the beginning of the pandemic, around 50% more soaps and detergents is released every day in wastewater from households, commercial activities, and medical institutions, comparing the pre-pandemic period (SanJuan-Reyes et al., 2021). Once in the aquatic environment, surfactants and disinfection by-products are persistent, bioaccumulative, and toxic to aquatic species [41].

Wastewater samples collected from the wastewater treatment plant (WWTP) of Athens (Greece), before (2019) and during the COVID-19 pandemic (2020), revealed a remarkable increase in antiviral drugs (170%), antibiotics (57%), and hydroxychloroquine (387%), which are most pharmaceutical drugs applied to treat COVID-19, along with paracetamol (198%) (Galani et al., 2021). In addition to the pharmaceuticals potential ecotoxicity (Galani et al., 2021), it can increase microorganism's antidrug resistance (ADR) (Kumar et al., 2021), thus imposing a severe threat to human and animal health.

Concomitantly, there is also a possibility of coronavirus transmission through urban water cycles (in bioaerosols or sludges) to natural environments (e.g., waterways and soils) (Kumar et al., 2020; Ji et al., 2021). For example, the SARS-CoV-2 virus can remain stable for up to 25 days, and highly contaminated freshwater systems can provide infectious doses (e.g., >100 viral copies per 100 ml of water) (Shutler et al., 2020). SARS-CoV-2 can also be found in soil (i.e., up to 550 copies/g), which persistence is highly dependant on soil parameters (e.g., mois-

ture) (Anand et al., 2021). The possible contamination routes on both soil and water systems remain, however, poorly covered, although being expected a potential infection of organisms on such contaminated sites.

The presence of SARS-CoV-2 in organisms raises concerns regarding cross-species transmission. In fact, coronaviruses such as SARS-CoV and MERS-CoV, have a long history of cross-species transmission (e.g., Zhou et al., 2018; Li et al., 2005); and the SARS-CoV-2 virus was already detected in a wide vertebrate host range (Barbosa et al., 2021), including pets and wild carnivores (Sharun et al., 2021). Reports of SARS-CoV-2 infection in domestic and wild animal species is getting increased attention to determine if SARS-CoV-2 (or related coronaviruses) can get established in animal populations, which may eventually act as viral reservoirs (Nabi and Khan, 2020).

The pandemic has also created new challenges for species that have become reliant on food discarded or provided by humans. For example, during the lockdowns, various urban-dwelling animals, like rats, gulls, and monkeys, were forced to find food outside urban areas (Rutz et al., 2020). In fact, an increase in aggressive synanthropic predators (e.g., crows) was observed in natural coastlines, which altered local animal assemblage structure (e.g., small mammals, reptiles, crustaceans) (Gilby et al., 2021). Concomitantly, reduced human presence in more remote areas may potentially expose endangered species (e.g., rhinos, or top-demanded species in illegal trade) to increased risk of poaching (as reviewed by Rutz et al., 2020).

Lockdowns and consequent disruption of food production and transportation chains have also affected animal farming and threatened food provision to populations from developing countries. It is predicted that the disruption of food production and transportation chains is resulting in higher human casualties from hunger and starvation than from the disease itself (FSIN, 2020), with a similar prediction extended to animal farming (e.g., aquaculture, aquaponics (Senten et al., 2020)). Besides, livestock that could not be transported to slaughterhouses for human food processing due to a combined lack of transportation and workers at the slaughterhouses resulted in crowded farms and, to some extent, to animal sacrifice and incorrect disposal of their carcasses (e.g., buried or incinerated), increasing potential biosecurity risks and detrimental effects on the environment (Marchant-Forde and Boyle, 2020).

Despite the improvement in air and water quality in the first pandemic trimester (with the potential to improve the quality of crops), the shortages on production products (e.g., seeds, fertilizers, pesticides), limited agricultural activities that required human involvement (e.g., planting, collecting), restrictions in transportation and movements of goods and workers, are all contributing to shortcomings in food availability and provisioning (Poch et al., 2020). In the longer run, higher emphasis might be given to local food production to reduce imports and, consequently, the transport of products. Such transition would reduce CO₂, but it can also lead to intensive cultivation of vulnerable areas and soil degradation if not properly managed.

Environmental implication of single-use plastics-is plastic pollution a major issue?

When considering the negative effect of the COVID-19 pandemic in the environment in the longer run, a significant share of the literature highlights “plastic pollution” as a major issue. Indeed, the COVID-19 pandemic has exacerbated the dependence on single-use plastics, particularly in the packaging, food safety, and healthcare sectors (Parashar and Hait, 2021). Although the general production of single-use plastics (SUP), mainly packaging, decreased drastically from April to June, it followed an increase when its production returned to “business-as-usual” (from July to October 2020) (EEA, 2021). E-commerce experienced an increase in revenue of 16% above “business-as-usual” levels between March and September 2020, which might have led to an increase in the volume of plastics used for packaging (an estimated addition of 11,400–17,600 tonnes of plastic packaging in the same pe-

riod) that was supposed to be targeted by the reduction plastic policies (EEA, 2021).

Another influence of the COVID-19 pandemic has been related to the increased use and consumption of personal protective equipment (PPE), such as face masks, goggles, and gloves, in medical settings and by common citizens. The use of specific PPE (namely face masks) became recommended or mandatory to avoid the spread of the virus (SARS-CoV-2) (Parashar and Hait, 2021). The worldwide high demand and consumption patterns for these items (which increased by more than 300%) resulted in considerable challenges to plastic waste management (Silva et al., 2020) and aggravated environmental plastic pollution (Silva et al., 2021). With a significant load of potentially infected medical plastic waste produced in a household environment, the international and statewide guidelines prioritised incineration and landfilling of ashes to ramp-up waste processing (as reviewed by Parashar and Hait, 2021). This fact has even raised illegal plastic waste disposal (e.g., open dumps or unregulated landfills) by 280% worldwide (Reportlinker 2021) which inherently alters adjacent habitats and promotes plastic leakage. COVID-19 plastic waste, particularly PPE items, is already piling up in natural environments due to plastic leakage from waste facilities or intentional littering (Silva et al., 2021c). In addition, the number of volunteers doing clean-ups decreased substantially (near 91% in the U.S. (Hart, 2021)). Therefore, an amount of 0.15 to 0.39 million tons of PPE waste has been forecasted as entering the ocean during the first year of the pandemic (Chowdhury et al., 2021).

Several monitoring studies on COVID-19 plastic waste, particularly PPE, have been conducted in several urban and natural areas (Table 1), where densities can vary from 0.001 items/m² up to 0.1 items/m² in beach transects. PPE densities and distribution are often related to population density frequenting the area, points of convergence of anthropogenic activity, and implemented interventions to deal with COVID-19. For example, in Peru, recreational beaches presented the highest number of PPE items (73%), followed by surfing (24.6%), fishing and inaccessible beaches (< 1%) (De-la-Torre et al., 2021). Toronto, Canada, presented a higher number of PPE items in parking lots of large grocery stores and hospitals than residential trails (ca 5 and 2 times higher, respectively) (Ammendolia et al., 2021). In the UK, PPE proportion accounted for up to 5% of plastic litter, whereas in the Netherlands and Sweden, the proportion of PPE did not generally exceed 1% (Roberts et al., 2021). Sweden even recorded no COVID-related litter in multiple months, which is not surprising as Sweden did not implement the usage of face masks or mandatory closures throughout the pandemic, opposite to what happened in, for instance, the UK (as reviewed by Roberts et al., 2021).

A schematic representation of sources, fate, and effects of PPE on natural biota can be depicted in Fig. 1. Briefly, PPE can directly affect organisms via, for instance, ingestion, entanglement, and nest materials in the case of birds; or can indirectly affect organisms through the release of hazardous contaminants (e.g., metals, plasticizers, surfactants as reviewed by Patrício Silva et al. (Silva et al., 2021c). Several species such as seagulls (*Larus* sp.), peregrine falcons (*Falco peregrinus*), crows (*Corvus corone*), white storks (*Ciconia ciconia*), foxes (*Vulpes vulpes*), cats (*Felis catus*), and dogs (*Canis lupus familiaris*) seemed to interact with PPE macro-litter (as reviewed by Hiemstra et al., (Hiemstra et al., 2021) and data available at <https://www.covidlitter.com>). Some interactions result in chronic effects, such as restricting feeding to the point of starvation, facilitating predation, exhausting the animal, causing suffocation, infections, severe wounds, and amputations (Silva et al., 2021c). In aggravated cases, it can even result in organism's death. PPE waste in the bird's nest structure can also alter thermal and drainage properties, influencing reproductive success (Thompson et al., 2020). In addition, as polymeric and lipophilic materials, PPE litter can adsorb environmental contaminants (Anastopoulos and Pashalidis, 2021) and pathogens (Luksamijarulkul et al., 2014), including SARS-type (Kasloff et al., 2020). Thus, frequent ingestion of PPE litter can decrease organisms

health due to physical effects and potential chemical body-burdens, as observed in Seagulls (Seif et al., 2018). Although the fraction of hazardous chemicals (e.g., hydrophobic organics) sorbed by plastic debris seems to be low compared to natural particles, particularly in aquatic environments (see Koelmans et al., 2016); their role as vectors increases when its higher mobility is considered, contributing to long-range environmental transport and affect remote locations (Gouin, 2021).

Littered PPE, along with other single-use plastic-based items such as wet wipes, can also be transported by weather conditions into drains and sewerage systems, resulting in potential blockages while entangled with other solids (e.g., leaf litter) (Silva et al., 2021b) and will also negatively affect water percolation and normal agricultural soils aeration, with potential repercussions on land productivity. Considering that landfilling increased significantly to deal with COVID-19 plastic waste (e.g., as in Tehran (Iran), by 35% Zand and Heir, 2020), it can result in significant geomorphological changes and, in the long-term, aggravate the release of hazardous contaminants through biogas and leachates, to the atmosphere or adjacent aquatic and/or terrestrial environments, respectively (Silva et al., 2021b). The high use and consumption patterns of plastics and the prioritization of unsustainable plastic waste options (i.e., incineration) are likely contributing to the increment of CO₂ (Klemeš et al., 2020).

There is scarce data about the potential degradation and toxicological effect of PPE. Buried (e.g., landfilled) or in water compartments, littered PPE will undergo fragmentation and biodegradation due to physicochemical and biochemical processes while releasing a myriad of micro(nano)plastics and leachable hazardous chemicals such as plasticizers, metals, organophosphate esters, as recently reported in laboratory conditions (Saliu et al., 2019; Sullivan et al., 2021; Wang et al., 2021; Fernández-Arribas et al., 2021). The only available data suggests that disposable face masks (as individual layers or as a blend) can easily decompose in natural topsoils (75% of the water holding capacity, 25 °C), with a mean residence time of 2 to 3 days, releasing approximately 3 to 5% of the total masque carbon as CO₂ (Knicker and Velasco-Molina, 2021). In addition, the release of polypropylene microfibres resultant from the mechanical fragmentation of disposable face masks (1 g/kg soil) decreased reproduction and growth of springtails (*Folsomia candida*) by 48% and 92%, respectively (Kwak and An, 2021). In earthworms (*Eisenia andrei*), acute exposure to such microfibres decreased esterases activity by 62% (enzymes actively involved in the resistance of several contaminants such as insecticides (Montella et al., 2012) and spermatogenesis (vital for earthworms reproduction) (Kwak and An, 2021). The effects observed could result from the physical damage caused by microfibres, as ingestion was observed for both macroinvertebrates; and/or due to the chemical toxicity induced by PPE leachates. Although the ecotoxicological effect of microfibres was studied in concentrations higher than the values reported in the environment, it does not rule out cumulative/generational adverse effects. An alteration of soil community structure and composition, in the long run, would impair essential soil ecosystem services and functions, resulting in significant ecological and economical damages.

Besides the above-mentioned effects, there is also an increase in the environmental footprint related to the massive production, distribution, and waste (mis)management of COVID-19 single-use-plastics (PPE). For example, the estimated carbon footprint of PPE distributed for use by health and social care services in England during 2020 first semester was approximately 106 thousand tonnes CO₂eq, representing 0.8% of the entire carbon footprint of health and social care in England during six months of normal activity (estimated at 27 million tonnes CO₂eq/year in 2018) (Rizan et al., 2021). Nevertheless, such estimations did not account for the "end-of-life" options of these items. Therefore, COVID-19 related single-use PPE plastics (SUP-PPE) and their ramifications (from production to waste management, persistence in the environment, adverse effects to different biological systems) are the major threats to environmental compartments on a short- and long-term basis.

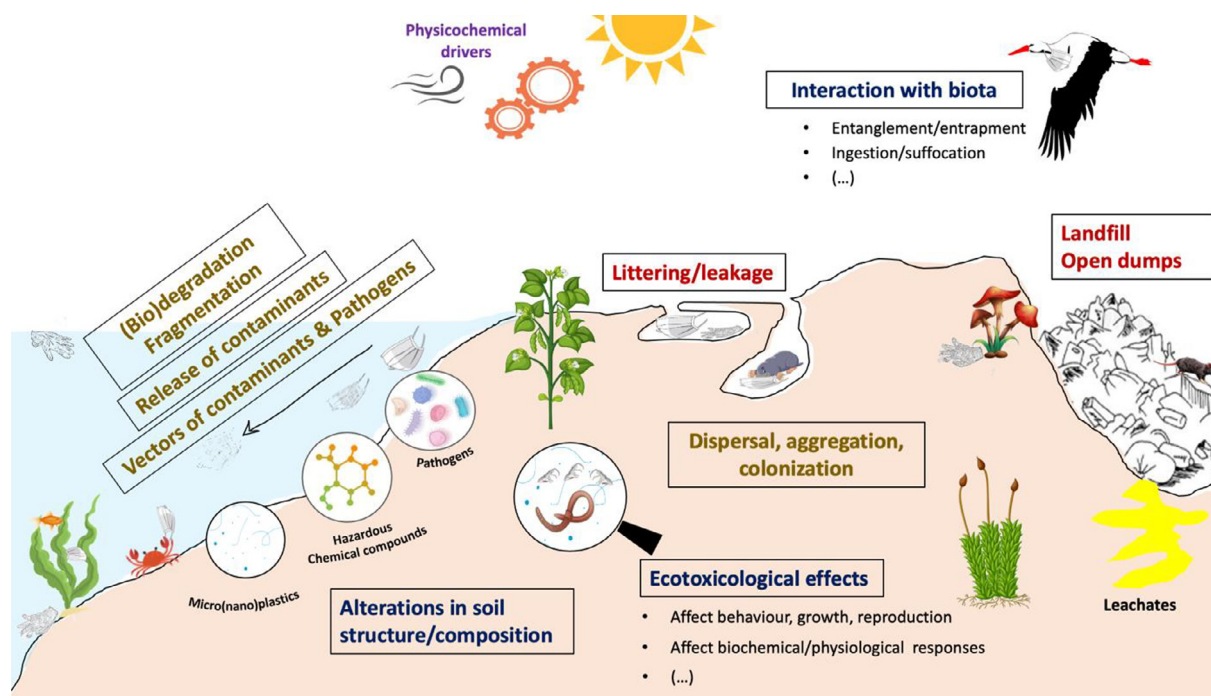


Fig. 1. Source, fate, and effects of personal protective equipment in aquatic and terrestrial environments.

Table 2

Occurrence and density of personal protective equipment in urbanized areas and natural environments during the COVID-19 pandemic.

Location	Sampling sites	Number of items	Refs.
Lima; Peru	11 beaches	7.44×10^{-4} items/m ²	De-la-Torre et al. (2021)
Jakarta bay; Indonesia	Cilincing and Marunda river mouths	~254.7 - 246 items/day	Cordova et al. (2021)
Kwale, Kilifi, Mombasa; Kenya	Beaches (sediments and water), and streets	Streets: 0.01 item/m ² Beaches: 0.1 items/m ²	Okuku et al. (2021)
Soko island; Japan	100 m beach	7×10^{-3} items/m ²	Stokes (2020)
Cox's Bazar; Bangladesh	One beach (13 sampling sites; 12 weeks)	6.29×10^{-4} items /m ²	Rakib et al. (2021)
Bushehr; Iran	Sandy beaches (S1, S4, S7-S9) Rocky beaches (S3, S5, S6)	~54 items/m ² for 40 days	Akhbarizadeh et al. (2021)
Toronto; Canada	Parking lots, hospitals, residential areas	0.001 items/m ² /day or 6.5 items/day. Parking lots and hospitals ($1.60-1.33 \times 10^{-3}$ items/m ²) Residential areas ($2.9-2.7 \times 10^{-4}$ /m ²)	Ammendolia et al. (2021)
Chile	12 tourist beaches from northern and central Chile	0.006 ± 0.002 items/m ²	Thiel et al. (2021)
Cape Town and Durban; South Africa	Urban environments	2271 (11.4 ± 4.4 items/100 m ² /day) to 3741 items (18.7 ± 9.6 items/100 m ² /day) but <1% comprised PPE.	Ryan et al. (2020)

Final remarks and future perspectives

COVID-19 pandemic is affecting the environment and human lives at a pace without precedents. The anthropause induced positive but short-term impacts at an early stage, such as reduced GHG emissions and decreased pressure on natural resources. However, those improvements fell short of the current sustainable goals, and soon as the human activities went back to “business-as-usual”, such environmental improvements receded, returning to their pre-COVID levels or, in some cases, aggravating, as observed for plastic waste mismanagement.

The recovery of the lost environment during COVID-19 lockdown indicates that the environmental degradation caused by humans is reversible, and mitigation strategies should be prioritised and implemented to recreate such “accidentally positive” scenarios. A good example is the concept of “smart city” (such as Singapore, Seoul, Helsinki and Zurich; <https://www.imd.org/smart-city-observatory/home/>). Such smart cities are implementing smart mobility (connected and free of GHG emissions) for their citizens, along with the construction of energetically efficient homes and buildings, integrated

technology to monitor wildlife and natural environments, to improve air and water quality, and for the implementation of efficient waste collection and treatment to reduce litter, waste of energy and resources, and costs.

Another step is to replace conventional plastics with greener alternatives (as reviewed by Iroegbu et al., 2021), as already prioritized by several international initiatives such as the European Strategy for Plastics in a Circular Economy (as reviewed by Silva et al., 2020). Considering PPE particularly, the use of reusable or biodegradable alternatives (e.g., cotton masks and gluten-based masks, respectively) have been incentivised, along with their proper disinfection (e.g., via steam) and discard on dedicated waste-bins collectors. Effective public health programs through a “One Health Approach” are also important in addressing and managing pandemic scenarios (Legido-Quigley et al., 2020). Governmental agencies have already adopted one Health framework in the ASEAN Member States (e.g., the Philippines and Vietnam), where early warning systems, wildlife surveillance, education and public awareness campaigns, and inter-agency coordination are being implemented with positive economic and social outcomes (e.g., Agency, 2020) Table 2.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have influenced the work reported in this paper.

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