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# Microplastics and other emerging contaminants in the environment after COVID-19 pandemic: The need of global reconnaissance studies

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## Abstract

Evidence of the increase of emerging contaminants in the environment due to the COVID-19 pandemic, such as personal protective equipment (PPE), disinfectants, pharmaceuticals, etc., has enlarged. Here we explain the variety of pathways of these emerging contaminants to enter the environment, including wastewater treatment plants, improper disposal of PPE, and runoff from surfaces treated with disinfectants. We also discuss the current state-of-art of the toxicological implications of these emerging contaminants. Initial research suggests that they may have harmful effects on aquatic organisms and human health. Future directions are suggested as further research is needed to fully understand the impacts of these contaminants on the environment and humans, as well as to develop effective approaches to mitigate their potential negative effects.

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## Introduction

COVID-19 constitutes an unprecedented global health, environmental and economic crisis. Since its detection in late 2019 up to the moment (23 December 2022), according to World Health Organization (WHO) (COVID-19) Dashboard [1], there have been 651.918.402 confirmed cases of COVID-19, including 6.656.601 deaths. The extent of the COVID-19 pandemic and the efforts to control the disease and treat the infected people has led to significant changes in the production and consumption of plastics, pharmaceuticals, and disinfectants as well as in the pattern of their residues in the environment. Early reports on the environmental effects of the pandemic registered an overall improvement in air quality (reduction of CO, NO<sub>2</sub>, NO<sub>x</sub>, PM2.5, PM10, and VOC levels), groundwater quality, beach cleanup, and noise pollution due to the confinement and cessation of many activities [2,3]. This improvement was clearly temporal. However, the pandemic also triggered a sudden increase in the global demand for personal protective equipment (PPE) (masks, gloves, gowns), disinfectants (bottled hand sanitizers, biocides, household disinfectants), and anti-COVID-19 pharmaceuticals (antibiotics, antivirals, glucocorticoids, etc.) [3]. To give an idea of its magnitude, during initial attempts to stop the spread of the virus, the WHO estimated that 89 million medical masks were needed worldwide monthly, along with 76 million examination gloves and 1.6 million sets of goggles [4]. Some reports consider that this contamination could also be temporary and will disappear with the pandemic. However, more than 2 years since cases were first reported, the COVID-19 pandemic remains as an acute global emergency [5]. All indications are that in time and in the best-case scenario, COVID will become a recurrent seasonal respiratory disease like the flu [6]. Therefore, the changes in the pattern of contaminants and the presence of new emerging contaminants related to the pandemic may be much more permanent than one might initially think.

On the basis that there is neither an established harmonized definition nor a complete list of the

compounds that are included in the term “emerging contaminant”, the US Environmental Protection Agency (EPA) defines an emerging pollutant as a chemical or material which because of a recent source that it originates, or because of a new pathway that has developed, and for which a lack of published health standards exist poses a perceived, potential, or real threat to the human health or the environment [7]. This definition can include plastics, microplastics, pharmaceuticals, disinfectants, viruses, genetic material and a long etcetera that would cover all products generated during COVID-19 due to their prevention and treatment.

The objective of this review is to investigate the occurrence of emerging contaminants increased by the COVID-19 pandemic in the environment and their potential impact on environmental health. This will provide valuable information on the potential pathways through which emerging contaminants may spread and accumulate in different environmental compartments. We will review the current state-of-the-art on the toxicological implications of these emerging contaminants, focusing on their potential effects on aquatic organisms. We will also examine measures to reduce their presence.

### Identifying the changes in emerging contaminants and microplastics before and during the pandemic

There are no official data on the production or use of medical waste but it is already demonstrated that the COVID-19 pandemic has worsened the environmental contamination by microplastics and other emerging contaminants. As mentioned in the Introduction, the use of PPE such as masks, gloves, and goggles has increased disproportionately during the pandemic. All these materials, in addition to the problem of the increased solid waste they represent, can generate microplastics in the environment. To give an idea, Sun et al. [8] estimated that only the face masks discarded throughout the year 2020 would lead to >1370 trillion microplastics entering the coastal marine environment globally, with a release rate of 396 billion microplastics per day. It is important to note that the COVID-19 pandemic has had a significant impact on waste generation, particularly in healthcare settings. The study by Peng et al. [9\*\*] estimated that by August 23, 2021, the total excess mismanaged waste generated during the pandemic ranged from 4.4 to 15.1 million tons globally. This excess waste was largely generated by hospitals, accounting for 87.4% of the total, while the usage of PPE by individuals contributed only 7.6%. In developed countries, plastic waste generated in hospitals, health centers, and other community facilities is treated and managed in accordance with applicable hazardous waste legislation (e.g., in the case of the European Union, Directive 2008/98/EC on hazardous waste). These legislations mostly involve incineration/disinfection of the

waste followed by secure disposal (e.g., sanitary landfill of the ashes). Incineration is not completely harmless, as it generates some toxic compounds such as dioxins and furans, the levels of which grow with the increase in materials to be incinerated [10]. However, several reviews about the use of plastic material in Europe during the pandemic consider PPE as the main source of plastic to the environment [11]. Medical waste is not treated in many developing countries, including India, Brazil, and China (between 11.5% and 76%, of these residues are not treated [9\*\*]). These countries still dispose of medical waste in landfills or open dumps. Landfills generate dust, fires, and biogas that contribute with microplastics (that can be further deposited) and greenhouse gases to air pollution. Leachates are also of concern, especially in times of heavy rainfall, capable of degrading these PPE and releasing micro and nanofibers along with hazardous chemicals [12\*\*,13]. Peng et al. [9\*\*] also estimated that ca. 26 thousand tons of pandemic-associated plastics have been released into ocean from 369 major rivers and their watersheds, Asia being the main contributor to this waste. This situation is not ideal but it is even less so because PPE used in households, such as face masks, are in part improper disposal on streets, roads, and beaches; subsequently, a proportion of these discarded face masks end up in landfills or soils and another enters the aquatic environment and, finally, the oceans [14]. Face masks can liberate microfibers and chemical additives (e.g., antimicrobials, skin protectors as nanoparticles, self-cleaners, plasticizers as bisphenol A, etc.), while the discarded masks in the aquatic environment would release more microfibers and adsorb various contaminants [15\*\*]. Wang et al. [16] recently reported the presence of discarded face masks in an urban river with a density of  $(8.28 \pm 4.21) \times 10^{-5}$  items/m<sup>2</sup>. Mohamed et al. [3] conclude that extensive usage of face masks increased the release of microplastics/nanoplastics (183–1247 particles piece<sup>-1</sup>) in land and water bodies. Pashaei et al. [17] assessed the microplastics predominance in 13 countries during COVID-19 showing that particles with a size of 1–2.5 mm and 2.5–5 mm accounted for half of the microplastics, and most abundant polymers were polypropylene, polyethylene, polystyrene, and polyethylene terephthalate, which are the plastics that cover >50% of medical plastics demand.

Emerging contaminants can be viruses and bacteria as well as chemical substances. Since the beginning of the pandemic, many studies have highlighted the role of urban wastewater treatment plants (WWTPs) in the spread of the virus excreted by the human body, which was detected early in wastewater and receiving water bodies [18,19\*\*,20]. This has also supported the hypothesis that the presence of feces in wastewater drainage may contaminate groundwater and be an emerging threat to water pollution leading to the spread

of COVID-19 [21]. As a counterpart, detection and quantification of COVID-19 in wastewater constitutes a powerful application of the wastewater based epidemiology (WBE) that act as an early warning system and achieves preventive recognition of hotspots of virus reappearance [22\*,23,24,25,26,27]. The analysis of microbiome profiling of wastewater through DNA metagenomic and RNA metatranscriptomic techniques can provide valuable insights into the potential presence of various microorganisms (bacteria, viruses, fungi) and their associated virulence and antibiotic resistance genes. Interestingly, Brumfield et al. [28] observed out of the 345 genera detected across the samples, only 14 were found to be positively correlated with the presence of SARS-CoV-2 RNA. This suggests that certain bacterial genera may be more closely associated with the presence and persistence of the virus in the community.

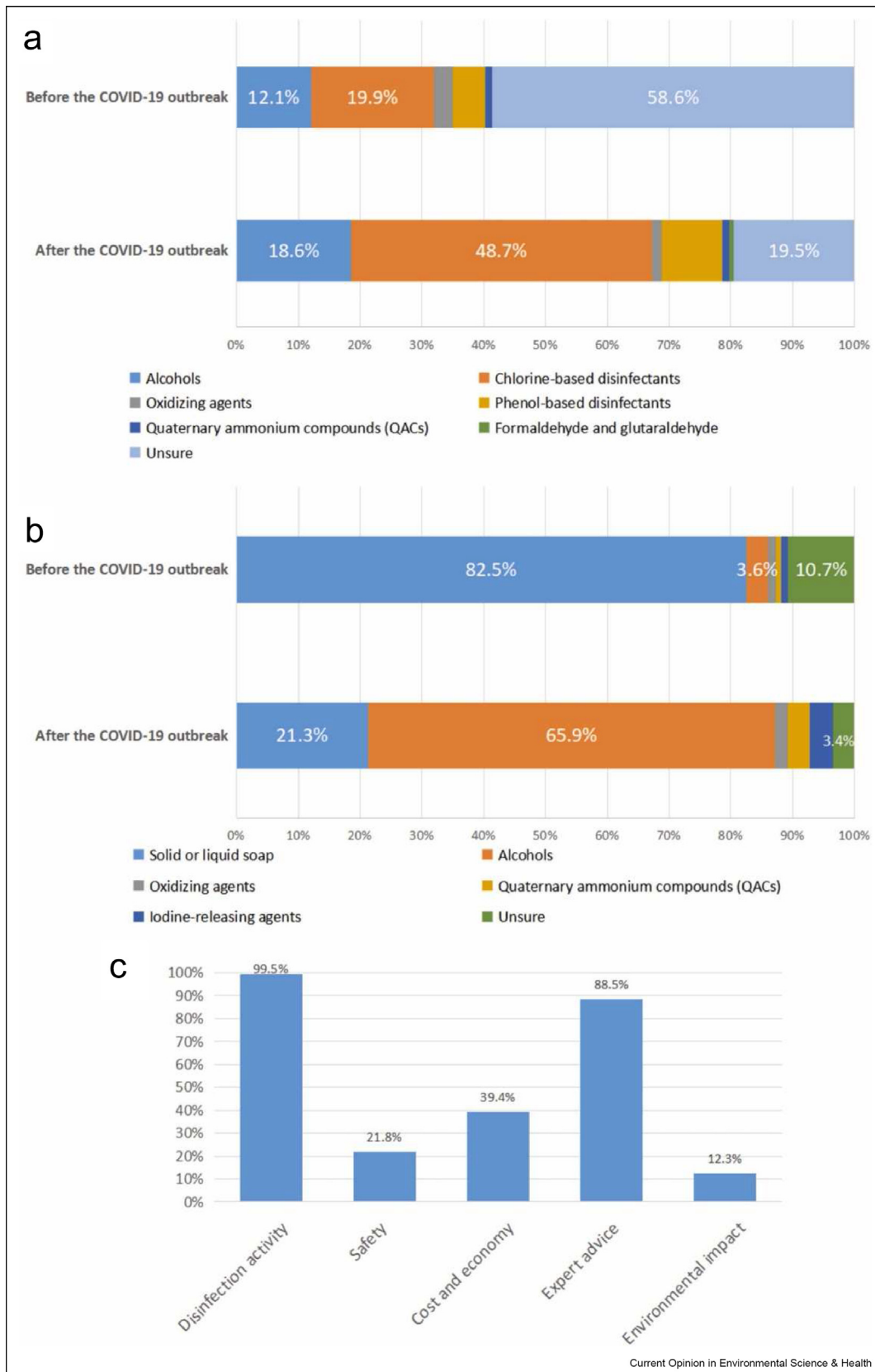
Although the application of WBE can expose unnecessarily the personnel to SARS-COV-2 since it requires routine sampling, the utility of the information obtained to fight against the pandemic compensates. To prevent the spread of COVID-19 among personnel involved in sampling or analysis, work is underway to develop different types of biosensors, the most promising of which are based on detection with nano-based magnetic materials due to their sensitivity [24,27,29]. At present it is still unknown for how long SARS-COV-2 can remain in water [29]. SARS-COV-1 (the most similar virus to SARS-COV-2) can survive for 2–4 days in sewage and wastewater at room temperature and for a more prolonged time at lower temperatures [22\*]. SARS-COV-2 was persistent for 1.4–3.3 days for 1-log and 2.9–6.5 days for 2-log of titer reduction of the virus in infecting wastewater [30]. This substantiates the limited persistence of this virus in water media. However, in the same study, a similar resistance was observed for the virus in tap water. It was also established that the SARS-COV-2 tends to be adsorbed onto particles and debris present in surface water and wastewater [22\*].

Wastewaters are also a well-known source of chemical pollutants, which are mainly originated from human activities [20,31]. The increase in the use of disinfectants (including disinfectants [32\*], hand sanitizers [33], and quaternary amines [34]) during the COVID-19 pandemic as infection preventive and control measures has been appealing all over the world [10,35–37]. To offer an overview on the nature of these disinfectants, there is an interesting questionnaire-based survey that investigated the impact of the COVID-19 outbreak on household disinfectant product consumption levels and behavior of 3667 Chinese residents [38]. The household disinfectant product consumption tendencies before and after the COVID-19 outbreak as well as the motivation of the disinfectants' consumption choice is presented in Figure 1. Chlorinated compounds at home and ethanol and cationic quaternary ammonium

compounds (QACs) as hand sanitizers have highly increased. Only 12.3% of the respondents considered the environmental impact of household disinfectant products as an important factor affecting their own current disinfectant consumption choice. This situation has resulted in a continuous and high emission of parent molecules in sewage and the generation of large quantities of degradation or toxic by-products that flow into wastewaters and, once in the WWTP, end up in the effluent or adsorbed to sludges, which may imply an increased chance of antimicrobial resistance emergence [39]. Alygizakis et al. [39] studied through WBE the effects of pandemic in Greek population and revealed increases in surfactants (+196%), biocides (+152%), cationic quaternary ammonium surfactants (QACs) (used as surfactants and biocides) (+331%). These results are consistent, as the QACs showing the greatest increase are in more than 200 products recommended by the US EPA for use against SARS-CoV-2 as active ingredients [34]. Important environmental problems can be originated by oxidizing disinfectants, such as chlorine that reacts with dissolved organic matter and other compounds to form disinfection by-products (DBP) that are not biodegradable. Liu et al. [40] focused their research on the well-known toxic DBP investigating the presence and distribution of trihalomethanes, haloacetic acids, and nitrosamines in rivers and seawater in Hong Kong. The study showed that total trihalomethanes concentration in seawater was significantly higher than that before the COVID-19 pandemic but below the established tolerance levels. Among the disinfection byproducts detected, bromoform in rivers and seawater poses the highest risk to aquatic organisms. Pharmaceuticals and other medical compounds present in wastewater can also react with these oxidizing disinfectants forming many new and more toxic DBP [41].

Before, during, and after the pandemic, the WBE has been widely used to assess behavioral changes (use of licit and illicit drugs, such as antidepressants, Cocainics, alcohol and tobacco, etc.) during the lockdown. In this regard, the results on licit and illicit drug use in America and Europe were quite heterogeneous and inconclusive. Data only point to an increase in the use of benzodiazepines and other antidepressants to alleviate the effects of confinement [42–46]. The massive use of pharmaceuticals against COVID-19, most of which had never been used before in such amount, has occurred, causing a sudden increase in the concentrations of these drugs in surface waters [47]. The first studies published after the start of COVID pointed to massive use of any type of pharmaceutical. However, data presented are sometimes not fully comparable, since the pre-pandemic data are from several years earlier and therefore the increase in drug concentration may be due to either, the COVID pandemic or the better coverage of health systems with time [17]. Further studies about the changes in consumption of different classes of pharmaceuticals

Figure 1



between several periods of time that included 2020 pandemic year have been highlighted in wastewaters of Athens, Greece [48] while the trend of consumption of pharmaceuticals during the pandemic has been studied in the wastewaters of New York, USA [49\*] and of Spain [50], in environmental surface waters around Wuhan, China [49\*] and in the sewage sludges in Connecticut, USA [45] as summarized in Table 1. These studies, which are more substantiated, point to a significant increase in anti-COVID-19 drugs (outlined in Table 2) and a certain increase in some substances that can alleviate the psychological pressure of home confinement (as reported for benzodiazepines), while other drugs show only small variations. These changes in the pattern of pharmaceuticals are not only reflected in the wastewater but also in the different aqueous ecosystems where wastewater is released. In this sense, Morales-Paredes et al. [51\*\*] found that the concentration of most of the drugs used in the treatment of COVID-19 increased during the pandemic in water bodies.

It must be taken into account that in wastewater treatment plants, pharmaceuticals, microplastics, and COVID-19 RNA are not completely eliminated. Many of these contaminants and their transformation products can end up not only in the wastewater released but also in the sludge, which is also used as organic amendment. Furthermore, the role of landfills in the environmental distribution of emerging contaminants, microplastics, and COVID-19 RNA should not be dismissed. Figure 2 summarizes how these sources can affect environment and especially soils, which are ultimately the receptors of many of these contaminants.

### Identified gaps and future research

There are still many knowledge gaps to be filled and one important challenge to be met regarding the presence of microplastics and other emerging contaminants in the environment. This is of concern on several fronts. One of them has to do with the nature of the contaminants themselves that in some instances is still unknown as well as in the potential effects of climatic and other conditions on their concurrence and behavior. This may be related to the lack of information about the release into the aquatic environment of some of them, such as, artificial nanoparticles that may be contained in face masks and other PPEs. No data is available. Or it can be due to the appearance of unknown metabolites or transformation products from the breakdown of parent compounds. In a recent study, Kumar et al. [55] established the concurrence of PPCPs, viruses, fecal bacteria, and metals in surface waters of Guwahati in monsoon (wet) and pre-monsoon (dry) seasons, showing that

PPCPs and viruses were at much higher concentrations during pre-monsoon than during monsoon. This pointed out the need to emphasize the effect of the seasonality in untreated urban water. Better understanding of this topic can only come from global reconnaissance studies.

Another possible area of concern is with respect to the distribution, transport, and fate of these COVID-19-related contaminants in the different environmental compartments and ecosystems. Soil is the compartment where contaminants adsorb to, and co-migrate with, detached soil particles in porous media. It is also a possible transmission route of SARS-COV-2 to human beings since their long survival in solid surfaces has already been pointed out [41]. Soils can become a significant reservoir of pharmaceuticals, disinfectant, microplastics, and microorganisms. This can happen due to various reasons, such as the use of sludges as organic amendments, irrigation with contaminated water, or incorrect disposal of pharmaceutical wastes. These contaminants once introduced into the soil, can be degraded to other more toxic products or persist having several negative impacts, such as altering soil microbial communities, disrupting nutrient cycling, and reducing soil fertility [56]. The contamination can also lead to the accumulation of pharmaceuticals in crops grown in the contaminated soil, which can then enter the food chain and potentially pose a risk to human health. Wang et al. [36] reviewed the fate of viruses and pharmaceuticals after being released into soil environments (including surface soil, the vadose zone, and groundwater), concluding that the heterogeneity and complexity of various physical, chemical, and biological processes were difficult to predict their fate. Only more studies under controlled conditions on the fate of contaminants in soils will provide a better understanding.

A third area of potential concern is to do with the biota/contaminants interactions, since they have the potential to induce ecotoxicological effects. Table 3 summarizes globally the main findings. Tagorti and Kaya [35] shed light on the genotoxic effects of microplastics determined in somatic cells of aquatic organisms and human peripheral lymphocytes as well as their hypothesized mechanism of action (oxidative stress, inflammation, and DNA repair disruption). Patricio Silva et al. [15] noted the COVID-19 face mask occurrence in diverse environments and their adverse physiological and ecotoxicological effects on wildlife. Similarly, Sun et al. [8] demonstrated that the copepods (crustacean) ingested the microplastics released from polypropylene face mask, causing a significant decline in their fecundity. This could produce a long-term domino effect on

The public's household disinfectant product consumption tendency. (a): the most preferred products for environmental disinfection in the home before and after the COVID-19 outbreak; (b): the most preferred products for hand sanitization before and after the COVID-19 outbreak; (c): factors affecting the public's current disinfectant consumption choice. Data shown as the proportion of respondents who agreed or strongly agreed the corresponding factor was important for their own disinfectant consumption choices. n = 3667. Reproduced from the study of Guo et al. [38] with permission from Elsevier.

Table 1

Selected studies performed by WBE that compared the use of several contaminants before and during the pandemic (before 2019 and during 2020).

Compounds study	Country	Ref.
<b>Licit and illicit drugs and antidepressants</b>		
Z-drugs, benzodiazepines, and ketamine	USA and Mexico	[42]
Use of illicit drugs, alcohol, and tobacco	Spain	[43]
Illicit drugs (amphetamine, methamphetamine, MDMA, benzoyllecgonine, and 11-nor-9-carboxy- $\Delta$ 9-tetrahydro cannabinol)	European cities (Netherlands, Belgium, Spain, Italy)	[45]
Antidepressant drugs	Spain	[44]
Drugs of abuse and antidepressants	Connecticut (USA)	[45]
<b>Pharmaceuticals occurrence and pathways in the context of COVID-19 pandemic</b>		
NSAIDs, antihypertensives, diuretics, antiepileptics, antilipidemics, antibiotics, analgesics, antivirals, anticancer drugs, contrast iodinated drugs, antidiabetics, antiallergic drugs, anti-ulcers, and other pharmaceuticals	Greece	[48]
Change of chemical content in WWTPs (antipsychotic drugs, illicit drugs, tobacco compounds, food additives, pesticides, biocides, surfactants, and industrial chemicals)	Greece	[39]
Suspected screening of 78 chemicals of interest, which included pharmaceuticals, illicit drugs, disinfectants, ultraviolet (UV) filters, and others	Connecticut (USA)	[45]
High-throughput analysis (28 substances, 6 major classes: antidepressants, antiepileptics, antihistamines, antihypertensives, synthetic opioids, and central nervous system stimulants)	New York (USA)	[49*]
<b>Trace anti-COVID-19 pharmaceuticals</b>		
Suspected screening (acetaminophen, darunavir, hydroxychloroquine, lopinavir, and oseltamivir selected as anti-COVID-19 pharmaceuticals)	Italy	[52]
Suspected screening and correlations with COVID-19 metrics for several identified chemicals as well as many unidentified features in the data, including three potential indicator molecules that are recommended for prioritization in future studies on COVID-19 in wastewater and sludge.	Connecticut (USA)	[46]
Hospital use of antivirals and sedo-analgesic drugs	Spain	[53]
Antibiotics (three macrolide antibiotics and ciprofloxacin)	Spain	[50]
Increased concentration of anti-COVID-19 pharmaceuticals in wastewater	World	[51**]
Dexamethasone	Europe & Asia	[54]

ecosystems. If anything is clear about COVID-19-related contaminants is that many facets are unknown yet. For example, the effects of disinfectants applied during the ongoing pandemic on non-target organisms remain undetermined. Muse et al. [54] studied the effects of dexamethasone in the aquatic organisms observing important differences between intraspecies (from  $\mu\text{g/L}$  to  $\text{mg/L}$ ) and among different species (fish > daphnia > algae). These authors highlighted the dependence of the effects on species biology, age, growth phase, methods of exposure used, and endpoints measured. Nannou et al. [49\*] also assessed the environmental risk for aquatic organisms of COVID-19 treatment agents (e.g., remdesivir and dexamethasone). Other studies not included in Table 3 because they just considered death of the animal [60,61\*\*] reported aid by models [e.g., ChemFate or Ecological Structure Activity Relationships (ECOSAR)] the risk to potentially exposed organisms providing preliminary data to assess and manage ecological health risks. These studies coincided at establishing that environmental concentrations reached in the environment can be hazardous for the three trophic levels algae, *Daphnia magna*, and fish.

One important point related to this area is the increase in discharge of antimicrobials (antibiotics, antibacterials, antivirals, etc.) that spread the environmental antimicrobial (and/or antiviral) resistance (AMR) [49\*,58\*\*,61\*\*,62\*\*]. For instance, before the pandemic, Azithromycin concentrations in surface waters were reported to be in the order of  $4.3 \text{ ng L}^{-1}$ , and during the pandemic, they increased up to  $935 \text{ ng L}^{-1}$  [51\*\*]. A study on the expansion of microbial resistance genes in the environment indicates that stress induced by high antibiotic concentration leads to altered gene expression in aquatic microbiota and contributes to the evolution of resistant species [58\*\*]. Given the problem of the increasing lack of effectiveness of antibiotics due to the increase of antibiotic-resistant pathogens, the situation described is serious and deserves special consideration. Disinfectants can have an effect on the spread of AMR. QACs disrupt bacteria cell membranes, and research has shown that their use can also select for antibiotic resistance in pure cultures of bacteria. The use of QACs in hospitals can lead to the development of multidrug-resistant bacteria [34]. Agathokleous et al. [57] collected evidence from multiple studies showing that chemicals used for major

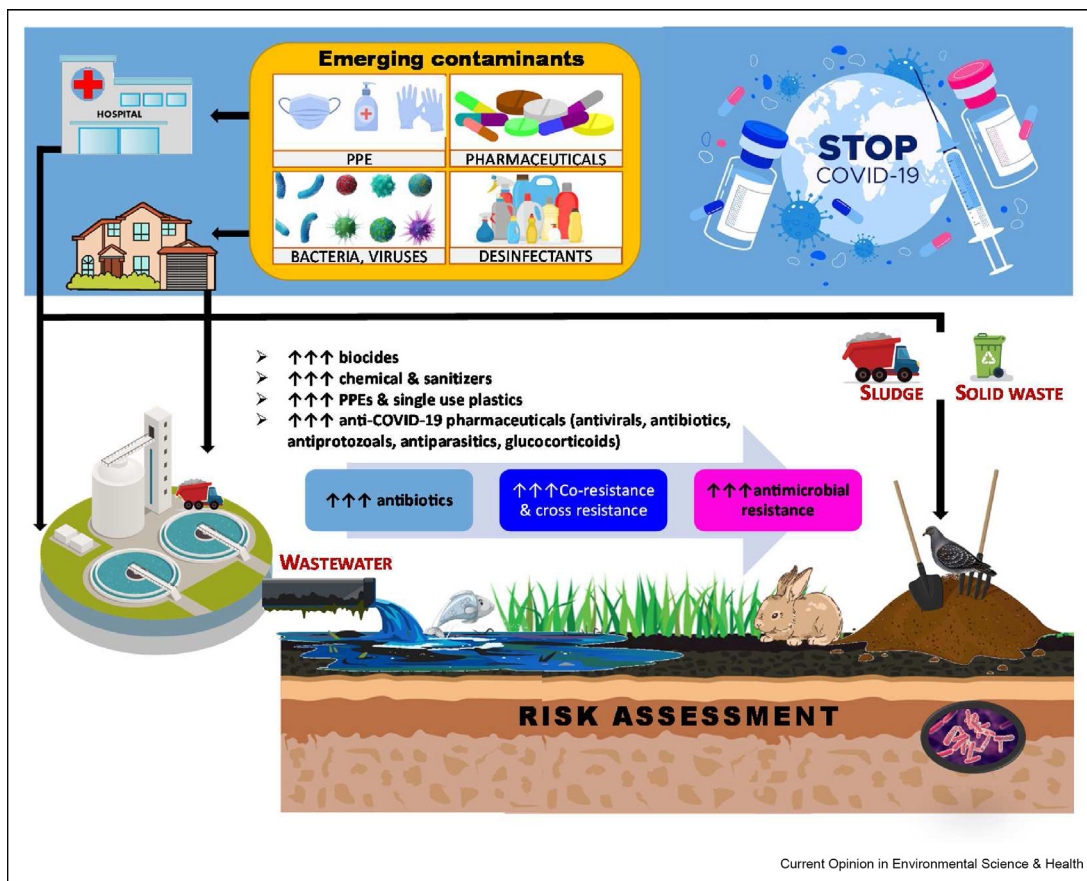
**Table 2**

**Summary of widely used or under trial phase potential candidate drugs for the treatment of COVID-19 patients across the globe [48,54].**

Drug Category	Drug name
Antivirals	Remdesivir
	Nelfinavir
	Favipiravir
	Lopinavir
	Ritonavir
Antimalarial	Osetamivir
	Chloroquine
Anti-inflammatory	Hydroxychloroquine
	Hydrocortisone
Antiparasitic	Dexamethasone
	Ivermectin
Antibacterial	Azithromycin
Analgesics	Paracetamol

disinfectant products can induce hormesis in various organisms, such as plants, animal cells, and microorganisms, when applied singly or in mixtures, suggesting potential ecological risks at sub-threshold doses that are normally considered safe. Among other effects, sub-threshold doses of disinfectant chemicals can enhance the proliferation and pathogenicity of pathogenic microbes, enhancing the development and spread of drug resistance. Real-world samples, however, contain a variety of chemicals, not only one specific group of chemicals, and the study of non-linear dose–response relationships induced by complex mixtures is challenging and practically difficult. There are still many knowledge gaps about the effects on the aquatic biota of these compounds alone or in mixtures. Animals have also been proven to be reservoirs for SARS-COV-2 this involves that virus could spread from humans to other animal species, termed reverse zoonosis, as is suspected for white-tailed deer in the United States [59]. SARS-COV-2 was also efficiently replicant in cats and ferrets and poorly replicant in dogs, pigs, chickens, and ducks [22\*]. The role that the release of viable particles of

**Figure 2**



Environmental release of COVID-19-related contaminants.



Table 3

## Toxic effects of microplastics and other emerging contaminants related to COVID-19 treatment.

Type of organism	Emerging contaminant	Toxic effect	Ref.
Cell culture Somatic cells aquatic organisms	Microplastics	Genotoxicity (oxidative stress, inflammation, and DNA repair disruption)	[35]
Human lymphocytes	Microplastics	Genotoxicity (oxidative stress, inflammation, and DNA repair disruption)	[35]
<b>Aquatic</b> Bacteria	Dexamethasone Antiviral drugs	Increasing bacterial doubling time Potential antiviral resistance Growth inhibition	[54] [49*]
	Disinfectants	Proliferation and pathogenicity of pathogenic microbes, enhancing the development and spread of drug resistance	[57,58]
Algae	Dexamethasone	↓↓ or ↑↑ growth and chlorophyll-a content	[54]
Sea anemone	Microplastics	Alteration in intestinal metabolism and gut microbiota ↑↑ inflammation.	[15]
Crustacean	Microplastics	↓↓ feeding activity ↓↓ growth and reproduction ↓↓ food intake ↓↓ body mass and metabolic rate ↑↑ adult mortality Adverse embryonic development No effects on survival and bacterial infection (PS) ↑↑ Mortality (PE) Physiological deformities Alteration in sinking rates	[8,15]
Crustacean	Dexamethasone	↑↑ mortality, ↓↓ reproduction ↓↓ population growth	[54]
Crustacean	Antiviral drugs	Growth inhibition	[49*]
Bivalves	Microplastics	Compromise filtration rates	[15]
Fish	Microplastics	Intestine alterations Gut inflammation Metabolism disruption Gut microbiota dysbiosis	[15]
Fish	Dexamethasone	↓ growth ↓ reproduction performance	[54]
Fish	Antiviral drugs	Liver damage ↑↑ Fish mortality	[49*]
<b>Terrestrial</b> Arthropod	Microplastics	Ingestion/egestion ↓↓ reproduction (48%) and growth (92%) No biochemical or behavioral alterations	[15]
Worm	Microplastics	Altered burrowing Altered feeding behavior Altered molecular genetic biomarkers Biochemical alterations (esterase activity dropped 62%; spermatogenesis declined to 0.8) No effects on survival Absence of pathological symptoms	[15]
Terrestrial mollusk	Microplastics	↓↓ food intake and excretion Damage in the gastrointestinal walls Oxidative stress.	[15]
Birds	Antiviral drugs	Wildfowl especially for the anti-influenza drugs, since birds host influenza virus (es).	[49*]
Ferrets	SARS-COV-2	Spread of SARS-COV-2 and reverse zoonosis High capacity of replication	[22*]
Cats	SARS-COV-2	Spread of SARS-COV-2 and reverse zoonosis High capacity of replication	[22*]
Deer	SARS-COV-2	Spread of SARS-COV-2 and reverse zoonosis High capacity of replication	[59]

**Table 3** (continued)

Type of organism	Emerging contaminant	Toxic effect	Ref.
Humans	Disinfectants	Affect the mucosal lining (inflammation, irritation, swelling, and ulceration of the respiratory tract) Skin dryness Risk of developing asthma, chronic obstructive pulmonary disease, impaired brain development, and infertility in children	[57]

virus in the environment can play is unknown. However, recently, the world health organization (WHO) established the concept of “One Health” recognizing that the health of humans, domestic and wild animals, plants, and the wider environment (including ecosystems) are closely linked and interdependent.

This goes to the heart of the challenge around COVID-19-related contaminants, right up to how to reduce their presence in the environment. There are a multitude of different aspects. In the case of improper disposal in landfills, not only governments but also consumers should be called upon to raise awareness of the need for proper disposal. The provision of better means for developing countries together with public awareness is the best solution that can be linked to the sustainable development goals. Neither virus nor emerging contaminants are fully eliminated in conventional WWTPs, since these plants were not originally designed for it. For SARS-COV-2 RNA removal, there is an important lack of data on i) comparative efficacy of various treatment processes, and ii) temporal variations in the removal efficacy in the backdrop of active COVID-19 cases. Interestingly, Kumar et al. [63] compared the removal efficacy of conventional activated sludge (CAS) and root zone treatments (RZT). CAS treatment exhibited better RNA removal efficacy than RZT. Disinfection seems less effective than the adsorption and coagulation for SARS-COV-2 removal. Results stress the need for further research on mechanistic insight on SARS-COV-2 removal through various treatment processes. Advanced oxidation processes (AOPs) remove recalcitrant pharmaceuticals, microplastics, and genetic material but the sophistication of the process and high cost keep them at the laboratory or pilot scale [26,27,64\*\*]. Promising results were shown using hybrid systems formed by the combination of biological treatment [membrane bioreactors (MBR), moving bed biofilm reactors (MBBR), constructed wetlands (CWs), activated sludge process (ASP), etc.] with adsorption-based or filtration-based processes, and various AOPs [64\*\*]. In this sense, laboratory scale studies concluded that adsorption and AOPs can remove up to more than 80% of azithromycin, chloroquine, ivermectin, and dexamethasone. Pilot-scale treatments by adsorption with powdered activated carbon eliminated 100% of azithromycin from

hospital wastewater. At full scale, treatment plants supplemented with ozonation and artificial wetlands completely eliminated Favipiravir and Azithromycin, respectively [51\*\*]. Ultimate technologies proposed to improve the removal of COVID-19-related pollutants are mesmeric nanobiotechnology, electrochemical oxidation, and membrane processes [26,27]. However, these technologies are far away to be implemented and require more study. In this challenge, there are also several aspects that are absolutely unknown. One of them is the percentage of emerging contaminants, microplastics, and virus RNA that remains retained in sewage sludge. In some cases, it is known that the treatments remove the contaminants from the water but retain them in the sludge that, as mentioned above, also returns to the environment in the form of organic amendment. The main challenge that remains is to reduce the release of these contaminants in the environment through a better elimination of solid wastes and improved treatment of wastewater. This can be achieved through research on new technologies that provide greener and more sustainable wastewater treatment, development of quality assurance tools, and implementation of global cooperation to achieve a solid understanding of relevant issues and concerns. The need to advance and better understand puts the spotlight on environmental reconnaissance studies as one of the most effective tools for expanding our knowledge and filling knowledge gaps.

## Conclusions

This compilation highlights the important changes in the occurrence of emerging pollutants in the environment. The main sources of these pollutants into the environment are wastewater and landfills, but the sludges derived from the wastewater treatment also can spread contaminants. There are still several knowledge gaps that need to be resolved regarding transformation of the products release to the environment as well as transport, fate, and seasonal distribution. There is also a wide range of research needs that needs to be addressed such as the interactions of these compounds with biota and potential toxic effects. Up to the moment, the evidence emphasizes the profound link between human and ecosystem health and the need to monitor and protect the human—animal interface considered as “critical fault

line” to minimize the threat to both. The increased presence of emerging contaminants used in the treatment of COVID, including antimicrobials, resulting in an increase in AMR is already well documented.

### Credit authorship contribution statement

**Yolanda Picó:** Writing – original draft, Investigation.  
**Damià Barceló:** Writing – review & editing.

### Editorial disclosure statement

Given his role as Editor-in-Chief of the journal, Damia Barcelo had no involvement in the peer-review of this article and has no access to information regarding its peer-review. Full responsibility for the editorial process for this article was delegated to Fang Wang.

### Declaration of competing interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: DAMIA BARCELO reports administrative support was provided by Catalan Institute for Water Research. Editor in chief of COESH.

### Data availability

Data will be made available on request.

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