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ECOTOXICITY OF SARS-CoV-2 AND EMERGING CONTAMINANTS: IMPACTS ON THE ENVIRONMENT AND PUBLIC HEALTH FROM THE ONE HEALTH PERSPECTIVE

ECOTOXICIDADE DO SARS-COV-2 E CONTAMINANTES EMERGENTES: IMPACTOS NO MEIO AMBIENTE E NA SAÚDE PÚBLICA SOB A PERSPECTIVA DA SAÚDE ÚNICA

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ABSTRACT

The increasing spread of environmental pollutants (biological, physical, and chemical) combined with limited knowledge about emerging contaminants poses a significant risk to both the environment and human health. SARS-CoV-2 has affected various sectors of human society (including biomedical, epidemiological, social, economic, political, cultural, and historical domains) particularly impacting the most vulnerable populations. This study aimed to assess, through the One Health perspective, whether and how the COVID-19 pandemic may affect ecosystems and what the direct and indirect repercussions are for human health. To this end, a narrative review was conducted using scientific publications available on Google Scholar, focusing on basic sanitation, types of pollution, and COVID-19. Findings indicate that SARS-CoV-2 and its viral particles have negatively influenced the biology of various organisms and may interact with the environment in poorly understood ways, including potential secondary transmission routes. Moreover, the virus appears to act synergistically with environmental pollution (air, water, and soil), enhancing both its transmission and its harmful effects. These observations highlight the urgent need for improvements at all levels of basic sanitation, proper waste management, enhanced treatment and disinfection systems, and the advancement of metagenomic research to support environmental monitoring and the prevention of future public health crises.

Keywords: Environmental surveillance. Basic sanitation. Environmental pollution. Public policies. Social vulnerability.

RESUMO

A crescente propagação de poluentes ambientais (biológicos, físicos e químicos) aliada à falta de conhecimento sobre contaminantes emergentes é um risco ao meio ambiente ee a saúde humana. O SARS-CoV-2 impactou diversos setores humanos (biomédico, epidemiológico, social, econômico, política, cultural e histórica), acometendo especialmente populações mais vulneráveis. Este estudo visou analisar, sob a perspectiva da Uma Só Saúde, se, e como a pandemia da COVID-19 pode afetar ecossistemas e quais as repercussões diretas e indiretas à saúde humana. Para tanto, performou-se uma revisão narrativa de produções disponíveis no Google Scholar sobre saneamento básico, os tipos de poluição e COVID-19. Evidenciou-se que o SARS-CoV-2 ou suas partículas virais tem

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influenciado negativamente a biologia de diversos organismos, podendo interagir com o ambiente de formas pouco compreendidas, incluindo rotas de transmissão secundárias. O vírus, ainda, tem atuado em sinergia com a poluição ambiental (ar, água e solo), intensificando a sua transmissão e seus efeitos deletérios. Assim, evidencia-se a necessidade de melhorias em todos os níveis do saneamento básico, na gestão adequada de resíduos, na melhoria dos sistemas de tratamento e desinfecção, além da realização de pesquisas metagenômicas para monitoramento ambiental e prevenção de futuras crises sanitárias.

Palavras-chave: Vigilância ambiental. Saneamento básico. Poluição. Políticas públicas. Vulnerabilidade social.

INTRODUCTION

The natural environment has undergone profound transformations, compelling living organisms to rapidly adapt to escalating ecological disturbances (Tuomainen; Candolin, 2011). Since the mid-twentieth century, the Industrial Revolution has fundamentally reshaped the global socioeconomic landscape, spuring urbanization (Wang et al., 2024); intensifying the extraction and exploitation of natural resources; increasing environmental pollution to hazardous thresholds; altering climatic conditions; and disrupting the balance between health and disease patterns (Power et al., 2018; Ahmed et al., 2021; Wang et al., 2024). These dynamics have also introduced anthropogenic stressors such as noise, light, and vibrations into ecosystems (Mcdonnell; Hahs, 2015). Due to urbanization with rapid urban population growth, environmental pollution has emerged as a critical public health issue in both developed and developing nations (Meo et al., 2021; Shovon et al., 2024). Urbanization has also increased spatial proximity among humans and animals—particularly companion species—thereby intensifying the risk of exposure to novel biological and/or zoonotic agents (Esposito et al., 2023). This is exacerbated by the evolution of pathogens induced by the development of novel chemical compounds (Lebarbenchon et al., 2008) and the genetic modification of microorganisms (Hanlon; Sewalt, 2021), which have enabled the creation of new drugs, but with risks to public health and the environment that remain insufficiently understood (Wang et al., 2024).

According to Wang et al. (2024), emerging contaminants (ECs) are newly recognized chemical substances or biological agents that are detected in the environment and are potentially dangerous to both human and ecosystems health, however, the risks associated with them remain insufficiently characterized. They encompass a broad spectrum - from novel pathogens such as SARS-CoV-2 to chemical compounds developed for the prevention and treatment of COVID-19 during the pandemic (Picó; Barceló, 2023; Wang et al., 2024). Their expanding environmental dissemination is a cause for concern, as the associations between ECs and natural factors act as cryptic drivers of biodiversity loss, as they can disrupt several fundamental biological processes, resulting in maladaptive physiological, psychological/behavioral responses to environmental conditions in wildlife and humans alike (Domingo; Marquès; Rovira, 2020; Angelier, 2022).

The World Health Organization (WHO) has recognized the intricate and interdependent relationships among human, animal, plant, and ecosystem health, formalizing this integrated understanding through the concept of One Health (Picó; Barceló, 2023). According to this concept, the continuous and dynamic interface between humans and other animals - whether domestic, agricultural, or wild - means that we are in a constant relationship, which includes shared environments as potential conduits for the emergence and transmission of diseases across species boundaries (Zappulli et al., 2020). In essence, the complex interconnections among human, animal, plant, and environmental health can have far-reaching implications not only for ecological stability, but also for economic resilience, and human physical, mental, social, and cultural health (Mackenzie; Jeggo, 2019) while humans have a reciprocal influence on ecosystems (Wang et al., 2024).

As a result of the COVID-19 pandemic, social isolation and the momentary suspension of many activities were were implemented as strategies to curb viral transmission (Wu; Leung; Leung, 2020) and ensure adequate access to healthcare services (Rafael et al., 2020). These interventions significantly altered the global patterns of consumption and waste generation, resulting in a temporary shift in the human ecological footprint. According to Picó and Barceló (2023), some environmental improvements were observed worldwide in this period, including enhanced air and groundwater quality, cleaner coastal zones, and reduced noise pollution. However, these gains were counterbalanced by a sharp rise in medical and plastic waste, incineration, a decrease in indoor air quality, the widespread use of disinfectants (e.g., household disinfectants, hand sanitizers, biocides), and anti-COVID-19 pharmaceuticals, such as antibiotics, antivirals, glucocorticoids, etc. (Faridi et al., 2020; Tagorti; Kaya, 2022; Picó; Barceló, 2023). The cumulative effect of these anthropogenic actions has made a chain effect on biotic communities, which, in turn, can also affect human health and well-being due to the intrinsic interdependence of these systems. As COVID-19 has become a recurrent seasonal respiratory illness (Murray; Piot, 2021), the resulting patterns of environmental contamination may be much more permanent than was initially anticipated.

Although an increasing number of studies have examined the direct and indirect consequences of human exposure to SARS-CoV-2 and/or its viral particles, there are still significant knowledge gaps about whether and how the COVID-19 pandemic on wildlife, and the potential manifestations in future outbreaks. Furthermore, given the possibility that environmental contamination by SARS-CoV-2 may exacerbate the impacts of pre-existing pollution, assessing the direct and indirect expected repercussions is an opportunity to anticipate actions that mitigate effects on living beings, whether human or not. To address these gaps, a comprehensive literature review was conducted using indexed databases, with the objective of synthesizing interdisciplinary scientific findings by the One Health perspective. This integrative approach extends beyond conventional inquiries into the virus's transmissibility, pathogenesis, and treatment, aiming instead to illuminate understudied dimensions and the interactions between SARS-CoV-2 and emerging contaminants in the environment. By adopting this perspective, this study seeks to promote a healthy and sustainable environment for all forms of life.

MATERIALS AND METHODS

In this study, we performed a comprehensive literature search through indexed databases, specifically Google Scholar. The review focused on academic publications from 2020 to 2025, encompassing original research articles, scientific notes, review papers, brief communications, discussion papers, and reports from authoritative sources such as the World Bank. It was used a broad range of keywords, including: COVID-19 pathogenesis; environmental pollution; SARS-CoV-2 infection; air pollution; water pollution; soil pollution; microplastic; wastewater; solid waste; pharmaceutical waste; biomedical waste; particulate matter; post-Covid syndrome; late COVID; ecotoxicology; emerging contaminants; epidemiology; Geography of Health; One Health; environmental impacts; public health; environmental surveillance; veterinary medicine; transmission route; vectors.

Initially, the literature search produced a substantial volume of published material. All retracted publications were excluded. The remaining works were categorized according to thematic relevance, disease characteristics (transmission, infection, pathogenesis), interaction with living organisms (human, aquatic, or terrestrial), the synergistic or antagonistic effects of environmental contaminants, and the type of pollution involved (air, water, or soil). The selected studies were then critically analyzed from ecological and public health perspectives, forming the basis of this narrative review. Additionally, in cases where contextual enrichment or thematic depth was necessary, peer-reviewed articles published prior to 2020 were incorporated into the results section to enhance interpretation and discussion.

ENVIRONMENTAL SURVEILLANCE AND THE DIFFERENT MANIFESTATIONS OF COVID-19

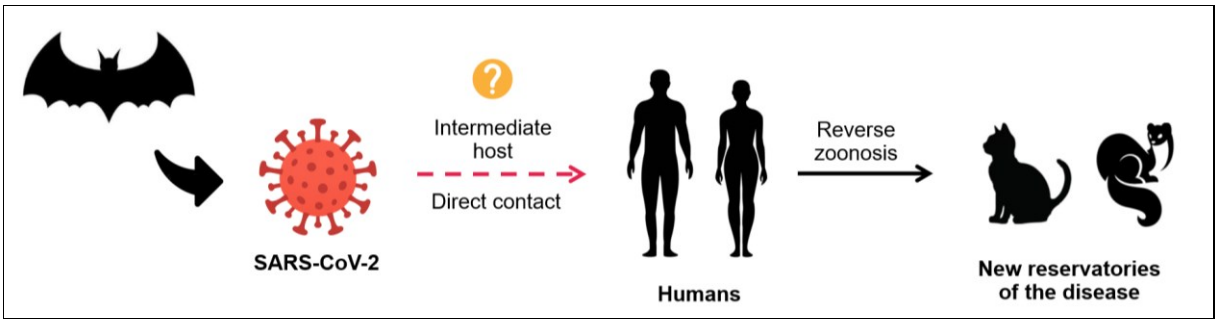
The SARS-CoV-2 (Family Coronaviridae, Genus *Betacoronavirus*) is the etiologic agent of COVID-19 (WHO, 2020), whose genus is composed of viruses that infect mammals (Manzini et al., 2021). The most recurrent transmission pathways of SARS-CoV-2 include direct contact with an infected person (Meyerowitz et al., 2021), inhalation of virus-laden respiratory droplets (Phan et al., 2020; Riou; Althaus, 2020), and exposure to contaminated environments containing aerosolized viral particles (Charlie-Silva et al., 2021; Graham et al., 2020). Additional transmission routes have been proposed, including fecal-oral and fecal-nasal pathways, mainly through aerosols generated from urine and feces, or touching contaminated toilet surfaces (Giacobbo et al., 2021; Jayaweera et al., 2020). This possibility is reinforced by the viral persistence on inanimate surfaces (metal, glass or plastic) for up to 9 days (Kampf et al., 2020). During this period, the virus can interact with non-human animals, potentially leading to adverse biological effects (Charlie-Silva et al., 2021; Kraus et al., 2022; Luz et al., 2022).

In humans, SARS-CoV-2 infection can present clinically in asymptomatic individuals, individuals with mild symptoms, individuals with acute respiratory disease or patients with pneumonia of varying degrees of severity (Lai et al., 2020). In symptomatic individuals, the clinical profile predominantly involves the respiratory and digestive systems. According to Lu et al. (2020), the main symptoms were fever (88.3%), cough (68.6%); myalgia or fatigue (35.8%), expectoration (23.2%), dyspnea (21.9%); headache or dizziness (12.1%); diarrhea (4.8%) and vomiting or nausea (3.9%). Most patients (86%) progress with favorable clinical outcomes; 14% require oxygen therapy in a hospital unit, and less than 5% require intensive care (WHO, 2020). Complications of the infection can progress to pneumonia, severe acute respiratory syndrome (SARS), cardiac or renal damage, secondary infection of shock, and cardiac, hepatic, and renal dysfunction (Guo et al., 2021; Huang et al., 2020). Mortality is usually related to the elderly, comorbidities, and critical cases (Dowd et al., 2020; Wu; Mcgoogan, 2020).

Post-COVID Syndrome in humans is known to include respiratory, cardiovascular, digestive and neurological complaints (Lechner-Scott et al., 2021; Oronsky et al., 2023). These manifestations are mainly due to the permeability of brain tissue to the virus (Zhang et al., 2020), immune hyperstimulation and neuroinflammation, but also due to psychological stress (Kempuraj et al., 2020), and the effect on the intestinal microbiota (Almeida et al., 2023). It is also known that SARS-CoV-2 can infect female reproductive organs (ovary, uterus, and vagina), and the hypothalamic-pituitary-gonadal axis, leading to infertility and various menstrual disorders (Madaan et al., 2022). In addition, female sex hormones (estradiol and progesterone) influence mast cell behavior, potentially leading to disorders related to female reproductive function (hormonal disorders, endometriosis progression, female fertility, and pregnancy progression). However, this relationship has not yet been proven as a post-COVID-19 pathology (Szukiewicz et al., 2022).

According to Tan et al. (2022), after the initial leap of COVID-19 from a zoonotic host to humans - possibly from an ancestral viral lineage that circulated in bats - COVID-19 has now acted as a reverse zoonosis, with significant transmission to domestic and wild mammals, which have consequently become reservoirs of the disease (Figure 1). Several animals are susceptible to coronaviruses, which can affect their respiratory tract (cattle, canids, chickens, marine mammals, murines, mustelids, non-human primates, wild ruminants, and pigs), the small intestine (cattle, canids, goats, cervids, horses, domestic and wild cats, chickens, raccoons, lions, leporidae, murines, mustelids, sheep, pigs), the large intestine (cattle and wild ruminants), causing neural lesions (domestic and wild cats, ferrets and mice), vasculitis (mustelids and wild cats), as well as damages occurring secondarily in the kidneys, liver, lymph nodes, pancreas, spleen, thymus, eyes and heart (Abdel-Moneim; Abdelwhab, 2020; Zappulli et al., 2020).

Figure 1 – Schematic summary of the evolutionary path of the SARS-CoV-2 virus, from its origin as an ancestral viral lineage circulating in bats to the zoonotic spillover from humans to other animals that have become new reservoirs of the disease



Source: the autors, 2024. It was created with images from ChatGPT.

About SARS-CoV-2, Mullick, Simmons, and Gaire (2020) point out that common experimental animals (e.g., mice, rats, rabbits, and guinea pigs) are not naturally sensitive to SARS-CoV-2 because they do not have ACE2 receptors. Conversely, ferrets have these receptors widely distributed in their respiratory tract (Shi et al., 2020), and the virus can be cultivated from their lungs (Zappulli et al., 2020). There is also evidence that dogs, pigs, chickens, and ducks are not susceptible to SARS-CoV-

2 (Shi et al., 2020). Despite growing studies, the consequences of releasing SARS-CoV-2 viral particles into the environment are not fully known (Picó; Barceló, 2023). Available studies suggest that the exposure of animals to the virus or its viral particles does not induce an infectious condition similar to that observed in humans. However, such exposure may still result in adverse biological effects in non-human animals in different ways, which are influenced by species-specific physiological traits, their biological classification and proximity to humans, and by the method of exposure used.

Aquatic and semi-aquatic organisms, for example, have their health affected by the peptide fragments of SARS-CoV-2, leading to damage to individuals with the potential to impact their natural populations (Malafaia et al., 2022). It has been shown that in Guppy specimens [*Poecilia reticulata* (Peters, 1859), Order: Cyprinodontiformes], exposure to SARS-CoV-2 viral particles altered their behavior, induced redox imbalance, affected their growth and development (Malafaia et al., 2022), Furthermore, Charlie-Silva et al. (2021) showed that the short exposure (24 h) of tadpoles to these peptides was enough to affect their health and memory since there was an increase in several biomarkers predictive of oxidative stress and an alteration in the activity of acetylcholinesterase. These observed effects show that exposure of these organisms to SARS-CoV-2 or its viral peptides can make them more susceptible to predation by not recognizing possible predators and directly impacting their vigor and physical performance. Thus, this exposure can affect the survival of the population and its dynamics in natural environments, influencing trophic chains and aquatic ecosystems as a whole.

Mammals, due to their evolutionary proximity to humans, tend to present symptoms more similar to those observed in SARS-CoV-2 infections. Shi et al. (2020) demonstrated that ferrets, cats, dogs, and pigs respond differently to intranasal inoculation of the virus. Ferrets exhibited viral replication in the upper respiratory tract and the presence of RNA in the intestine; cats presented respiratory infection; dogs showed low susceptibility; and pigs were not infected (Shi et al., 2020). Although mice are not naturally susceptible (Mullick; Simmons; Gaire, 2020), the administration of virus fragments induced cognitive deficits and enzymatic alterations in male mice, with greater sensitivity in those of the C57Bl/6J lineage (Luz et al., 2022). In females of the same lineage, pre-gestational exposure to virus proteins caused behavioral, hepatic, reproductive and intestinal disorders (Nunes et al., 2025a), in addition to neurochemical changes with an impact on maternal behavior (Nunes et al., 2025b). Infusion of the spike protein into the brain also induced late cognitive effects and neuroinflammation (Fontes-Dantas et al., 2023).

About environmental surveillance for SARS-CoV-2, it is known that both cats and ferrets are susceptible to the virus, can replicate it efficiently and transmit it to other individuals of the same species (Halfmann et al., 2020; Richard et al., 2020). Additionally, Xiao K. et al. (2020) indicated that 68% of wild pangolins in China and Malaysia were infected with Pangolin-CoV, a virus similar to SARS-CoV-2. This virus poses a potential public health threat, particularly if the wildlife trade is not effectively controlled (Huang, Su, Chen, 2024). The surveillance of the virus in these species should therefore be considered as a complement to erradicating COVID-19 in humans (Richard et al., 2020; Shi et al., 2020), and as an essential component of environmental control strategies targeting COVID-19 and similar future zoonotic diseases.

In light of these issues, the potential for zoonotic transmission of COVID-19 underscores the need for more comprehensive evaluations of the disease's ecological and environmental consequences. Such assessments should aim to clarify the impacts on ecosystems and explore the emergence of new forms of human–nature interactions that may sustain viral circulation in the environment. This includes identifying additional susceptible species, potential reservoirs of infection, and indirect environmental factors—such as the effects of climate change—that may facilitate new zoonotic spillovers. In this context, a holistic understanding of the interconnections between human, animal, and environmental health is essential for the development of integrated strategies aimed at mitigating cross-species transmission and improving outcomes in both public and veterinary health (Sellars, Bernotas, & Sebo, 2021). To this end, recent studies have highlighted the use of metagenomics and bioinformatics as promising auxiliary tools for the early detection of emerging infectious disease outbreaks (Wani et al., 2024).

VIRAL PERSISTENCE IN THE ENVIRONMENT

The persistence of SARS-CoV-2 on various surfaces depends on the type of contaminated material and the duration of exposure. Xu et al. (2023) further indicated that the virus's half-life on plastics ranges from 4 to 10 hours at 22 °C and can extend up to 4.6 days at 5 °C. Additional contamination sources include the use of sewage sludge as an organic amendment, irrigation with contaminated water, and improper disposal of personal protective equipment (PPE), such as disposable face masks. Medical waste, in particular, may serve as a reservoir for pharmaceuticals, disinfectants, microplastics, and microorganisms, potentially altering microbial communities, disrupting nutrient cycles, and reducing soil fertility (Picó & Barceló, 2023). In many countries, including India, Brazil, and China, medical waste often remains untreated and is discarded in landfills or open dumps, posing risks to the environment, wildlife, and human health (Peng et al., 2021; Khoo et al., 2021). Additionally, large quantities of hand sanitizers were released into terrestrial and aquatic environments during the pandemic (Atolani et al., 2020). Another essential factor in assessing the health risks associated with contaminated water is how long SARS-CoV-2 or its viral particles can remain in aqueous environments.

According to the evaluated studies, another critical factor for viral persistence is the impurity content of the water. Within the same temperature range (20–26 °C), the inactivation of viable SARS-CoV-2 is faster in mineral water, filtered seawater, wastewater, and river water than in drinking water, i.e., it decays more quickly in complex matrices than in simpler ones. This highlights the need to consider the physicochemical and biological composition of the water, as well as the effect of detergents, enzymes, and particle filtration when carrying out persistence tests (Mahlknecht, 2022). Variables such as dissolved solids and pH can significantly influence viral stability. For instance, a lower ratio of volatile solids to total solids (e.g., river water) can increase viral adsorption to suspended particles, thereby enhancing persistence (Picó; Barceló, 2023). Moreover, proper filtration and treatment of water contaminated with viral particles or RNA effectively reduce the concentration of these contaminants across different water matrices, limiting viral dissemination and interaction with pre-existing pollutants (Mahlknecht, 2022).

AIR POLLUTION, RESPIRATORY DISEASES AND COVID-19

Air pollution is the cause of several major environmental issues, including acid rain, intensification of the greenhouse effect, depletion of the ozone layer, and climate change. It results from a combination of meteorological factors, industrialization levels, and regional topography and has been identified as the leading environmental cause of disease and premature death worldwide (Frontera et al., 2020; Zhao; Liu; Gyilbag, 2022). Pollutants can be deposited on pasture and vegetation and subsequently ingested by animals, or they can be generated by animal handling itself, in which pathogenic microbes, endotoxins, odors, and dust are aerosolized and can, therefore, be inhaled by caretakers or animals (Catcott, 1961). In plants, pollutants can impair or inhibit vital physiological processes, as well as directly or indirectly contaminate plant-derived foods (Mudd, 2012). In animals, exposure to air pollution may predispose to respiratory and cardiovascular diseases (Izah et al., 2024), and result in the accumulation of toxic residues in meat, milk, and eggs, even in the absence of clinical symptoms (Newman; Schreiber; Novakova, 1992). Cui et al. (2003) further observed that individuals infected with SARS, a virus similar to SARS-CoV-2, were 84% more likely to die if they lived in a heavily polluted áreas, due to compromised immune defenses. Additionally, it can be associated with toxic metals (Skalny et al., 2020), causing even bigger toxicity.

Despite the importance of air pollution, this review found no studies linking it with exposure to SARS-CoV-2 in non-human animals or plants. In humans, as observed in other respiratory diseases, epidemiological studies have shown that it can increase the incidence, severity, and mortality associated with SARS-CoV-2 infection (Copat et al., 2020; Hassan et al., 2021; Zhao; Liu; Gyilbag, 2022). Furthermore, they indicated that the exposure to air pollution, especially particulate matter ($PM_{2.5}$ and PM_{10}) and nitrogen oxides (NO_2), can contribute to higher rates of infection and mortality from COVID-19, as well as increase its transmission (Frontera et al., 2020; Setti et al., 2020). This happens because atmospheric aerosols can carry the virus (Van Doremalen et al., 2020), and also induce pro-inflammatory, oxidative and immunological mechanisms in the lungs (Contini; Costabile, 2020). Other studies suggest that the exposure to pollutants distorts adaptive immune responses towards bacterial/allergic immune responses, as opposed to antiviral responses, which would predispose populations to develop immunopathology associated with COVID-19, worsening the clinical picture (Woodby; Arnold; Valacchi, 2021). So, although initially there was a general improvement in air quality due to the reduction in levels of CO, NO_2, NO_X, particulate matter ($PM_{2.5}$ and PM_{10}), and VOCs during the pandemic (Picó; Barceló, 2023), with the end of social isolation measures and the return to work, there was a massive return of the emission of air pollutants, with a consequent increase in transmission and deaths from viral respiratory diseases.

Although the association between air pollution and mortality from respiratory diseases is well established, there is still a need for clarification regarding confounding factors such as age and pre-existing medical conditions. Accurately quantifying premature mortality attributable to air pollution remains a challenge, particularly in regions where air quality is not monitored, and the toxicity of particles varies according to their source (Tuomisto et al., 2008). Furthermore, the main sources of pollution vary by country, region, and land use, ranging from residential emissions (India and China), agricultural emissions (eastern USA, Europe, Russia, and East Asia) to traffic and power generation emissions (much of the USA) (Lelieveld et al., 2015). Additionally, socioeconomic status can play a role in the epidemiology of illnesses and deaths associated with exposure to air pollution (O'neill et al., 2003). Therefore, a better understanding of these factors will reduce global mortality related to these causes. In addition, maintaining good air quality can help prevent COVID-19 and other respiratory diseases, thus constituting an integrated approach to epidemic prevention, public health promotion, and the principles of the One Health framework.

BASIC SANITATION

COVID-19, solid waste, and soil contamination

Soil is a possible route of transmission for COVID-19, as the virus can survive for a long time on solid surfaces, as well as being adsorbed and combined with detached soil particles in porous media (Parveen; Chowdhury; Goel, 2022). Soil quality has been negatively impacted as the generation of household waste (Sharma et al., 2020; Zand; Heir, 2020) and hospital waste (Sangkham, 2020; Yang et al., 2020) has increased because of social isolation and prophylactic measures/treatment of the disease. A significant portion of this waste was single-use plastic items (e.g., plastic bags, food packaging, and personal protective equipment, among others) (Alava et al., 2022), which may also function as vectors for the SARS-CoV-2 virus (Kampf et al., 2020).

As plastics from discarded materials degrade, they produce macro-, micro-, and nanoplastics, which are ubiquitous in the environment and can have various ecosystem or health implications for living organisms, mainly aquatic and terrestrial biota (Boyero et al., 2020; Costigan et al., 2022). In this process, they increases their surface area, can adsorb and concentrate persistent organic pollutants, toxic metals (Wright; Kelly, 2017), and pharmaceutical residues, amplifying their toxicity (Pashaei et al., 2022), and also acting as vectors for harmful pathogens, invasive species (Oberbeckmann et al., 2015; Alava et al., 2022) or some pollutants listed in the Stockholm Convention for their potential adverse effects (Wright; Kelly, 2017). Specifically, COVID-19, exposure to these substances can lead to greater susceptibility and greater severity of the disease, as well as complicate patient recovery (Domingo; Rovira, 2020). They can also cause human immunotoxicity (Quinete; Hauser-Davis, 2021).

Both plastics and other associated pollutants can bioaccumulate and biomagnify in organisms, causing their mortality, impairing their growth and condition (Boyero et al., 2020), inducing genotoxic effects in aquatic organisms (Tagorti; Kaya, 2022), impacting the reproductive performance of some organisms (Sussarellu et al., 2016), being trophically transferred, and triggering behavioral changes (Araújo; Malafaia, 2021). Boyero et al. (2020) highlight that amphibians can be an essential link in the trophic transfer of microplastics from aquatic to terrestrial environments. These trophic effects can also reach humans (Ahmed et al., 2019; Ali et al., 2022), which are the main routes of human contamination, but which can also occur through skin contact and inhalation (Ali et al., 2024).

Although the environmental relevance of the association between microplastics, toxic metals, and COVID-19 is recognized, few studies have investigated their ecotoxicological effects in aquatic or terrestrial ecosystems. Ferreira et al. (2023) evaluated this interaction in *Poecilia reticulata*, without observing synergistic, antagonistic, or additive effects between the contaminants. However, the absence of effects may be related to methodological limitations, since the microplastics remained at the bottom of the aquarium, outside the niche occupied by the species. In addition, the association with SARS-CoV-2 increased the adsorption of impurities by microplastics, altering their size and availability. These findings suggest greater susceptibility of benthic organisms and reinforce the importance of investigating the environmental effects of genetic or protein components of the virus, aiming at mitigation and conservation strategies for non-human animals (Charlie-Silva et al., 2021).

Wastewater and SARS-CoV-2

Although classical transmission of COVID-19 remains the predominant route, studies suggest potential secondary pathways of infection through contact with domestic sewage or contaminated water, including aerosols generated in pumping and wastewater treatment systems, as well as faulty plumbing connections. Evidence shows the presence of SARS-CoV-2 in feces, urine, and anal swabs of infected individuals, including asymptomatic or clinically recovered patients, with viral RNA detectable up to 33 days after symptom onset. The virus has been detected in wastewater across several countries, particularly where sanitation infrastructure is inadequate, contributing to secondary transmission. In this context, Wastewater-Based Epidemiology (WBE) has proven to be an effective tool for monitoring viral spread, detecting mutations, and providing early warnings of new outbreaks. However, its implementation in low- and middle-income countries requires adaptation due to the often deficient and overloaded sewage treatment systems.

In several countries, less than 30% of the sewage generated is treated before being discharged into streams (Rodriguez et al., 2020), more than 70% of the Earth's surface is covered by water (WSS, 2019) and the magnitude of the COVID-19 pandemic (Gonzaga et al., 2020; Barlow et al., 2021), there is a concern about the possible health impacts on biota, especially aquatic organisms, as a result of exposure to the virus and the presence of the genome and other viral structures in water. Studies evaluating the toxicity of SARS-CoV-2 peptides in aquatic organisms have helped to clarify the ecotoxicological potential of peptide fragments of the virus in non-target organisms, especially aquatic organisms. These studies have shown that the interaction between SARS-CoV-2 structures and non-human animals in the aquatic environment can, in itself, induce a variety of negative biological responses, marked by an increase in biomarkers predictive of oxidative stress and cholinesterase alterations [*Physalaemus cuvieri* tadpoles (Charlie-Silva et al., 2021; Silva et al., 2021)] and changes in locomotor and olfactory behavior [*Culex quinquefascitus* (Mendonça-Gomes et al., 2021)]. In addition, changes in growth/development, genomic instability, and DNA damage have been reported in *Poecilia reticulata* (Malafaia et al., 2022), as well as various morphological and immune response changes in zebrafish (*Danio rerio*) (Tyrkalska et al., 2023).

Nevertheless, relatively little attention has been given to the potential effects of aquatic contamination by SARS-CoV-2 on terrestrial organisms. These organisms have generally been used to assess their susceptibility to viral infection and their roles in spreading COVID-19 (Tiwari et al., 2020; Audino et al., 2021; Delahay et al., 2021). In a study aimed at evaluating the effects of direct (intraperitoneal) exposure to peptide fragments of SARS-CoV-2 in male mice (Swiss and C57Bl/6J strains), Luz et al. (2022) reported neurotoxic outcomes, including memory déficits, with the C57Bl/6J strain showing greater sensitivity to this exposure. Although this study demonstrades that terrestrial mammals may also exhibit ecotoxicological responses, it is important to note that the exposure method (intraperitoneal injection) does not reflect natural environmental conditions. Furthermore, a generational and fitness-based analysis should be carried out to infer ecological impacts with greater certainty, including the evaluation of offspring. In this context, the reports by Yang et al. (2022), Pitol et al. (2023), Javanbakht et al. (2024), and Tandukar et al. (2024) on the persistence of viral RNA in aquatic systems, together with the evidences presented by Luz et al. (2022) and Nunes et al. (2025a, 2025b), underscore the need for further investigations into the ecotoxicological effects of SARS-CoV-2 peptides on aquatic and terrestrial organisms, even in the post-pandemic period, when the risk of direct contamination has dimished. In addition, SARS-CoV-2 poses an ecotoxicological risk to biota, potentially impacting the dynamics and distribution of their populations (Luz et al., 2022), alerting us to the need for an ecological assessment of this issue.

Biomedical and pharmaceutical waste

Adopting the WBE strategy made it possible to assess behavioral changes in the population during and after the COVID-19 pandemic. During the pandemic, there were a reduction in the use of industrial chemicals and tobacco products (Alygizakis et al., 2021); and a increased use of sanitizers and medicines (Alygizakis et al., 2021; Picó; Barceló, 2023). Therefore, there has been a sudden increase or decrease in the concentrations of these substances in wastewater and, consequently, in surface water or other aqueous systems into which the waste flows, reflecting changes in environmental and ecological conditions (Picó; Barceló, 2023).

The intensified use of sanitizing products has led to various health risks for users (e.g., contact dermatitis, dehydrated skin, accidental poisoning, chemical burns, respiratory difficulties, and even carcinogenic effects) as a result of accidental or excessive exposure, and their flammability (Atolani et al., 2020; Guo et al., 2021). Oxidizing compounds, such as chlorine, have been widely used to prevent and control the coronavirus (Mahlknecht, 2022), but, in nature, they can react with dissolved organic matter in surface waters, generating by-products that are harmful to biota (e.g., trihalomethanes and haloacetic acids) (Atolani et al., 2020). Moreover, chlorine disinfectants are highly toxic since they can bioaccumulate; cause respiratory and digestive damage; is associated with cancer, developmental and reproductive disorders, or can lead to the death of terrestrial (birds, mammals) and aquatic animals (Parveen; Chowdhury; Goel, 2022). Besides, the excessive and improper use of antibiotics, hand sanitizers, and antiseptic soaps can lead to endocrine disruption and cause an increase in microbial resistance (Atolani et al., 2016; Kumar et al., 2023).

Pharmaceutical waste, which is among the most environmentally hazardous practices, comes from non-steroidal anti-inflammatory drugs, antibiotics, beta-blockers, anti-epileptic drugs, blood lipid-lowering agents, antidepressants, hormones, antihistamines, and X-ray contrast media (Pashaei et al., 2022). This is made worse by the fact that hospital wastewater is always a source of pathogenic micropollutants such as microorganisms, toxic chemicals, and antibiotic residues, which are often discharged into the municipal wastewater collection system without any pre-treatment (Pourakbar et al., 2022). The risk of these substances having an impact on the environment is directly proportional to their concentration in various environmental compartments and increases with inadequate management since conventional treatment systems are unable to remove these contaminants from water altogether (Morales-Paredes; Rodríguez-Díaz; Boluda-Botella, 2022), ultimately seeping into groundwater (Kumar et al., 2023). This is worrying, as they are persistent pollutants that are not very biodegradable (Morales-Paredes; Rodríguez-Díaz; Boluda-Botella, 2022) and can bioaccumulate or biomagnify, affecting both human health and the ecosystem (Pashaei et al., 2022). When they reach different aqueous matrices, especially groundwater, they become difficult to control and mitigate in the environment.

The continuous and high emission of emerging contaminants, mainly sanitizers and pharmaceuticals, and their toxic by-products into the sewage end up in the effluent of Centralized Wastewater Treatment Plants (WWTPs) or adsorbed in sludge, which implies a greater chance of the emergence of microbial and/or viral resistance to these products and drugs (Picó; Barceló, 2023). This is a global concern since antimicrobial-resistant infections already caused at least 700,000 deaths/year in 2019, and there was already a trend that, by 2050, this rate would increase to 10 million deaths/year and cause catastrophic damage to the global economy (WHO, 2019). In addition, most disinfectants are irritating and corrosive to the mucous membranes of the respiratory and digestive tracts (Dumas et al., 2019), posing a severe threat to the environment and life.

Despite reports of wildlife deaths due to the massive spraying of disinfectants to disinfect public areas in China (Nabi et al., 2020), there are few studies on the direct and indirect consequences of the increased emission of emerging contaminants during the pandemic on biota, especially non-target organisms of COVID-19. Knowing that neither the virus nor other emerging contaminants are eliminated in conventional WWTPs (Picó; Barceló, 2023), and considering that SARS-CoV-2 RNA tends to remain in WWTP sludge or untreated wastewater (Pourakbar et al., 2022) and can stay for up to 33 days in the environment (Table 1), the interaction of this genetic material with the sludge microbiota can also induce the emergence of microorganisms and variants that are more resistant to sanitizers. However, there is still no research evaluating the effect of the interaction of these pollutants with SARS-CoV-2 and/or viral particles on the biota.

SOCIAL VULNERABILITY, ENVIRONMENTAL POLLUTION AND COVID-19

Historically, the various endemics and pandemics have disproportionately affected the poorest and most marginalized populations, who are more socially and economically vulnerable due to their precarious living conditions and limited access to adequate healthcare, income, and education (Acharya, 2022). The spread of COVID-19 has produced far-reaching biomedical, epidemiological, social, economic, political, cultural, and historical impacts on the global population (Chakraborty; Maity, 2020; Huang et al., 2020; Barlow et al., 2021; Naseer et al., 2023; Khan et al., 2024). Notably, worldwide economic crisis triggered by the pandemic has increased the proportion of people living in extreme poverty, and malnutrition (Jackson et al., 2021), as well as heightened the vulnerability of those already at critical risk of COVID-19 (Sumner; Ortiz-Juarez; Hoy, 2020). Moreover, the pandemic has significantly undermined mental health, as social isolation, unemployment, confinement, and the loss of loved ones have contributed to elevated levels of stress, anxiety, depression, and suicide rates. This, in turn, has placed a greater financial and psychological burden on surviving family members and exacerbated food insecurity (Tagorti; Kaya, 2022). Combined with malnutrition - whether due to caloric deficiency or excess, or the lack of essential nutrients - these factors have likely intensified psychological distress during the pandemic (Saunders; Smith, Stroud, 2011), and led to alterations in the immune system, further increasing susceptibility to infectious diseases among these populations (Spoede et al., 2021).

Worldwide, low-income communities have experienced higher mortality rates influenced by factors such as overcrowded living conditions, employment that does not allow remote working, and limited access to healthcare services (Hawkins; Charles; Mehaffey, 2020Typically, individuals from lower-income backgrounds are compelled to reside in areas with greater environmental challenges, often located on the outskirts of cities or in regions unsuitable for habitation, such as hillsides and informal settlements (White; Guikema; Logan, 2021; Hartono et al., 2022). Consequently, pre-existing environmental issues - such as insufficient access to clean water, limited sunlight, inadequate temperatures, high humidity, exposure to natural disasters, stressful life events, and poor sanitation - further increase the vulnerability of these populations (Tagorti; Kaya, 2022). Furthermore, spatial segregation exacerbates health disparities by intensifying psychosocial stressors, including insecurity, anxiety, social isolation, socially dangerous environments, bullying, and depression (Marmot; Wilkinson, 2001).

In the United States, ethnic minorities and low-income groups have been disproportionately affected by higher COVID-19 infection and mortality rates (Van Dorn; Cooney; Sabin, 2020). Additionally, impoverished communities face increased exposure to pollution due to limited access to basic sanitation and elevated indoor air pollution from domestic sources - such as cooking fuels, cleaning products, and poorly ventilated living spaces - which heightens their risk of severe illness from infections like COVID-19 (Briggs, 2003). The disparity in health outcomes and social vulnerability is even more pronounced in developing countries. There, the convergence of poverty, weak or poorly enforced environmental regulations, and insufficient investment in technology leads to elevated pollution levels. This situation is further complicated by the complex and poorly understood relationships between contaminants and health effects (Briggs, 2003), contributing to millions of premature deaths annually and widespread environmental degradation (Wang et al., 2024).

Since social determinants of health are fundamental for characterizing and monitoring a population’s health status, public policies aimed at coping and recovery strategies must consider the specific needs and vulnerabilities of the most disadvantaged groups. This approach is essential to mitigate disproportionate impacts and promote a more just and resilient society (Marmot et al., 2008). From this perspective, Barrozo et al. (2020) proposed a Geographical Context Socioeconomic Index for Health Studies (GeoSES) to synthesize relevant socioeconomic information to contextualize population health, assess and monitor inequalities, and guide the strategic allocation of resources and services. GeoSES also facilitates the creation, implementation, and execution of more efficient and equitable intersectoral public policies, ultimately improving overall health outcomes and reducing disparities. The index is evaluated across different federative levels - municipal, state, and federal - and aligns with key population health indicators such as education, mobility, poverty, wealth, income, segregation, and deprivation of resources and services. Covering 46 variables, GeoSES serves as a comprehensive measure capable of indicating relative risks of mortality from preventable causes (Barrozo et al., 2020).

Although GeoSES is a vital tool for health management, it is essential to integrate the expertise of various fields of knowledge – such as medicine, veterinary science, environmental science, and public health - to effectively reduce the risks posed by environmental contaminants (ECs) and enhance the well-being of all organisms (Wang et al., 2024). This need becomes even more pressing considering that, to some extent, the COVID-19 pandemic can be viewed as an indirect consequence of global environmental changes—including soil degradation, ozone depletion, pollution, and urbanization—that have profoundly impacted both the environment and human health (Chakraborty; Maity, 2020). By equipping the state with more practical and effective tools, it can respond more efficiently to health crises, ensuring the right to health, promoting equity and social justice, guaranteeing all citizens decent living conditions, and universal access to essential services - particularly during times of public health emergencies.

FINAL CONSIDERATIONS

Studies on the ecotoxicological effects of SARS-CoV-2 show that, although this virus is mainly associated with respiratory and enteric diseases in humans, its viral particles can also negatively affect the physiology, behavior, and even reproductive health of organisms exposed in aquatic and terrestrial environments. These impacts have the potential to compromise the fitness of individuals, affect populations, and alter the balance and dynamics of ecosystems. Despite advances in this field, investigations to date have focused primarily on exposure to viral particles from the original SARS-CoV-2 strain, limiting understanding of the effects of viable and recombinant variants. In addition, papers have focused almost exclusively on aquatic organisms, disregarding possible impacts on terrestrial and soil organisms, especially through exposure to wastewater treatment residues. It is also worth noting the methodological difficulty in precisely controlling the viral dosage administered in the experiments, which reinforces the need for more realistic and standardized protocols that more accurately simulate environmental exposure scenarios.

Another aggravating factor is the exponential increase in emerging contaminants during the COVID-19 pandemic, such as plastic waste, biomedical waste, and pathogens. These pollutants can persist in the environment even after treatment and act as secondary sources of virus transmission. The degree of toxicity resulting from the interaction between these contaminants and SARS-CoV-2 is not yet known exactly, nor are the synergistic or antagonistic effects on the biota. Additionally, there is a plausible concern about the role of vectors as possible environmental disseminators of the virus, especially in highly contaminated areas. Populations in situations of social and economic vulnerability are disproportionately exposed to these risks, which increases their susceptibility to zoonotic diseases and increases the possibility of reverse transmission to domestic or wild animals.

In light of this scenario, further interdisciplinary research is urgently required to elucidate the environmental consequences of the COVID-19 pandemic, to develop accessible and effective technologies for contaminant treatment, and to formulate public policies that promote socio-environmental equity. This context also underscores the pressing need for improvements in basic sanitation infrastructure, proper waste management, and the enhancement of treatment and disinfection systems. Moreover, the advancement of metagenomic research is essential to support environmental monitoring efforts and to strengthen preparedness for future public health crises. Only through coordinated and integrative efforts by governments, scientific institutions, and civil society will it be possible to mitigate environmental impacts, and safeguard human, animal, and ecosystem health in a comprehensive and sustainable manner. Future research should prioritize the assessment of long-term ecological consequences, the resilience of affected ecosystems, and the development of nature-based and socially inclusive solutions to ensure preparedness for similar global challenges.

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