Since January 2020 Elsevier has created a COVID-19 resource centre with free information in English and Mandarin on the novel coronavirus COVID-19. The COVID-19 resource centre is hosted on Elsevier Connect, the company's public news and information website.

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Environmental challenges of COVID-19 pandemic: resilience and sustainability – A review

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ABSTRACT

The emergence of novel respiratory disease (COVID-19) caused by SARS-CoV-2 has become a public health emergency worldwide and perturbed the global economy and ecosystem services. Many studies have reported the presence of SARS-CoV-2 in different environmental compartments, its transmission via environmental routes, and potential environmental challenges posed by the COVID-19 pandemic. None of these studies have comprehensively reviewed the bidirectional relationship between the COVID-19 pandemic and the environment. For the first time, we explored the relationship between the environment and the SARS-CoV-2 virus/COVID-19 and how they affect each other. Supporting evidence presented here clearly demonstrates the presence of SARS-CoV-2 in soil and water, denoting the role of the environment in the COVID-19 transmission process. However, most studies fail to determine if the viral genomes they have discovered are infectious, which could be affected by the environmental factors in which they are found.The potential environmental impact of the pandemic, including water pollution, chemical contamination, increased generation of non-biodegradable waste, and single-use plastics have received the most attention. For the most part, efficient measures have been used to address the current environmental challenges from COVID-19, including using environmentally friendly disinfection technologies and employing measures to reduce the production of plastic wastes, such as the reuse and recycling of plastics. Developing sustainable solutions to counter the environmental challenges posed by the COVID-19 pandemic should be included in national preparedness strategies. In conclusion, combating the pandemic and accomplishing public health goals should be balanced with environmentally sustainable measures, as the two are closely intertwined.

1. Introduction

Since 2019, the world's public health has been seriously threatened by a novel infectious disease of the coronavirus family (SARS-CoV-2), which was first identified in Wuhan, China (Maalouf and Maalouf, 2021). To date (March 18, 2022), the COVID-19 confirmed cases had reached 464,809,377 resulting in 6,062,536 deaths across 222 countries worldwide (WHO, 2022). SARS-CoV-2 (severe acute respiratory syndrome coronavirus 2) was identified as the virus responsible for COVID-19 which belongs to the family Coronaviridae, Betacoronavirus genus, and subgenus Sarbecovirus (Yang et al., 2021). These viruses are 65–125 nm in diameter with single-stranded RNA as genetic material surrounded by an envelope (Ciotti et al., 2019).

Rapid transmission of novel SARS-CoV-2 mainly via droplets and aerosols and its infection through respiratory routes are the leading causes of increased hospitalizations and deaths. Studies have reported

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the presence of SARS-CoV-2 in stool samples of COVID-19 infected patients suggesting the possible transmission of SARS-CoV-2 via the fecal-oral route (Xiao et al., 2020). Direct discharge of hospital sewage, human excreta, domestic sewage, and wastewater to streams and rivers results in the secondary transmission of SARS-CoV-2 through the water. Moreover, the dumping of solid wastes such as domestic waste, human disposable hygiene products, hospital wastes, and managing of bio-solids from wastewater treatment plants (WWTPs) in landfills have increased the risk of SARS-CoV-2 transmission through leachate (Anand et al., 2022a). The use of wastewater for irrigation purposes and land application of sewage sludge on agricultural soils as an organic amendment has also been deemed as exposure routes for SARS-CoV-2. The new coronavirus (or its fragments) in aquatic systems represents the potential toxicity to aquatic biota (Charlie-Silva and Malafaia, 2022). Most of the detection methods for SARS-CoV-2 in different environmental compartments often do not assess the viability of the detected virus, thereby providing inadequate information on the role of water, wastewater, and other environmental compartments in virus transmission. The wastewater-based epidemiology (WBE), i.e., the detection and quantification of SARS-CoV-2 genetic material in wastewater, has been identified as a possible early warning tool that can be used to monitor the current pandemic status to determine future outbreaks (Bogler et al., 2020).

At the beginning of the pandemic, health sectors and other authorized organizations disseminated information on various protective measures, through directives and guidelines to be followed by communities to control the spread of COVID-19 (WHO, 2020b). Protective measures were heavily relied on to combat the COVID-19 pandemic without realizing its unintended environmental consequences. For example, during the pandemic, frequent and excessive use of hand sanitizers containing ethanol and isopropyl alcohol may adversely impact living microorganisms and aquatic species (Dhama et al., 2021). The residual chlorine released from disinfectants could react with organic substances present in the environment, thereby producing carcinogens such as trihalomethanes and haloacetic acids (Poursadeqiyan et al., 2020).

The unexpected fluctuations in waste generation have also arisen as one of the major challenges faced by the world during the pandemic. Medical wastes, including clinical wastes containing human or animal blood, excretions, and other disposable materials such as syringes, needles, plastic trays, gloves, face masks, aprons, bottles, and cups, have added a considerable volume to solid waste systems during the pandemic ((Dey et al., 2022; Kalantary et al., 2021). The use of pharmaceutical products, including antibiotics and cytotoxic drugs, has increased unabatedly during the outbreak. These drugs eventually end up in the environment and may potentially perturb the ecology and adversely affect human health (Subpiramaniyam, 2021; Anand et al., 2022b). The relatively long viability of SARS-CoV-2 on surfaces makes medical wastes a possible route for secondary transmission of COVID-19. Therefore, medical waste should be considered hazardous, and special care should be taken during its storage, disposal, handling, and treatment (Dharmaraj et al., 2021). According to one estimate, the COVID-19 outbreak has generated 1.6 million tons of plastic waste per day worldwide (Benson et al., 2021). This situation has adversely affected municipal solid waste management systems, mainly in developing countries. During waste collection, separation, recycling, and treatment, it is necessary to pay more attention to the guidelines introduced by health sectors to manage COVID-19 waste properly.

The global COVID-19 pandemic has sparked a heated discussion about probable long-term consequences on environmental sustainability. With the COVID-19 global crisis, attaining United Nations Sustainable Development Goals (SDGs) mainly on clean water and sanitation (SDG 6) and ending poverty by 2030 (SDG 1) would be an enormous challenge (Barbier and Burgess, 2020). Numerous research studies have examined the impacts of COVID-19 on the environment and mitigation efforts from different perspectives (Benson et al., 2021; El-Ramady et al., 2021; Hannah et al., 2020; Usman et al., 2020). Some studies documented the role of environmental factors in COVID-19 transmission and fatality rates (Mohapatra et al., 2021; Westhaus et al., 2021). Table 1 summarizes the key objectives and findings of previous reviews onCOVID-19 and the environment. Careful scrutiny of these studies revealed that most have only examined one aspect of the pandemic, such as the role of environmental factors in the spread of COVID-19 and vice versa. Therefore, a critical and comprehensive review of studies on the effects of COVID-19 on the environment is much needed to fill the knowledge gap. The current research aimed to fill this gap by investigating the impacts of COVID-19 on the environment (water quality, waste generation, and handling, and ecological health), as well as examining how the environment affected the virus, the main routes of transmission, and the preventative measures, with related to the main environmental matrices. The objective of the present review is to show how COVID-19 and the environment are both unsustainable threats to one another.

To conduct this review, databases including Scopus, PubMed, and Science Direct were extensively searched and all studies published until March 2022 were considered.. The literature search was thoroughly conducted by identifying relevant peer-reviewed literature consisting of reviews and original articles, conference proceedings, and book chapters. Keywords such as "SARS-CoV2", "COVID-19", "Transmission", "Soil", "Water", and "Environment" were used for conducting a literature search. The World Health Organization (WHO), the Centers for Disease Control (CDC), and the Ministry of Health's published guidelines, and other recognized organizations' publications, were also considered in this study.

2. Environmental occurrence of SARS-CoV-2

2.1. Occurrence of SARS-CoV-2 and related CoVs in the environmental matrices (soil and water)

The infectivity of a virus is determined by how long a particular pathogen survives outside the host's body (Lahrich et al., 2021). Seven coronaviruses have been confirmed to date that has been deemed infectious to humans causing minor to severe health effects. SARS-CoV-2 showed the highest environmental stability and transmissibility among these viruses, with a higher reproductive number (Ro) ranging from 1.40 to 6.49, which indicates that one infected person could infect 1.40–6.49 people (Bhowmick et al., 2020). The ability of SARS-CoV-2 to remain stable in different environmental compartments under different environmental conditions raises concerns about the potential transmission of SARS-CoV-2 via water, soil, bio-aerosols, food, and other environmental media. In this context, research on the occurrence, persistence, detection, transmission, and inactivation of SARS-CoV-2 in different environmental matrices is highly needed.

2.1.1. Environmental exposure routes – virus transmission

Several studies have reported the persistence of SARS-CoV-2 in the human gastrointestinal tract suggesting human excreta could be a new potential transmission route of SARS-CoV-2 (Amirian, 2020). The existence of coronavirus in stool samples of infected patients has been confirmed in previous studies even before the COVID-19 outbreak. The nucleic acid of SARS-CoV-1 had been found in the patient's urine and excreta samples that remained viable for 29–30 days (Xu et al., 2005). Hung et al. (2004) concluded that a maximum number of 10^7 SARS-CoV RNA copies could be present in mL of fecal matter and 2.5 x 10^4 copies/mL in urine. Fecal excretion and release to the environment were identified as the main transmission route for environmental contamination of MERS CoV and SARS CoV (Yeo et al., 2020; Zhou et al., 2017). Scientists have reported the presence and replication of SARS-CoV-2 in the patient's digestive tract, upper esophagus, adsorptive enterocytes of the ileum and colon, and gastric, duodenal, and rectal epithelia (Hamming et al., 2004; Zhang et al., 2020a). Further, a study by Xiao et al.

Table 1
Summary of literature review.

Title	Objectives	Key findings	Reference
Indirect effects of COVID-19 on the environment	Aims to show the positive and negative indirect effects of COVID-19 on the environment, particularly in the most affected countries such as China, USA, Italy, and Spain	A significant association between contingency measures for COVID-19 and improvement in air quality, clean beaches, and environmental noise reduction has been observed	(Zambrano-Monserrate et al., 2020)
COVID-19 pandemic and environmental pollution: A blessing in disguise?	To understand the relationship between the COVID-19 pandemic and environmental pollution	Pollution in some of the epicenters of COVID-19 such as Wuhan, Italy, Spain, and USA, etc. has reduced up to 30% due to lockdown where mobility is reduced up to 90%	(Muhammad et al., 2020)
Novel coronavirus disease 2019 (COVID-19) pandemic: From transmission to control with an interdisciplinary vision	Aims to present all the aspects connected with this pandemic, from virus diffusion mechanism to health information, from economic and social impacts to measures to reduce the pandemic spread	There is a need for the establishment of an international health-care trans-multi-disciplinary workforce devoted to investigating, mitigating, and controlling the existing and future viral events is important	(Anand et al., 2021c)
COVID-19 outbreak: Migration, effects on society, global environment and prevention	To assess the impact of COVID-19 on society and the global environment, the possible ways in which the disease can be controlled, and to implement a global strategy for COVID-19 prevention and control	COVID-19 affected society and the global economy It also has affected the global environment	(Chakraborty et al., 2021)
Observed and Potential Impacts of the COVID-19 Pandemic on the Environment	To provide an early overview of the observed and potential impacts of COVID-19 on the environment	The COVID-19 pandemic has led to numerous environmental impacts, both positive and negative	(Cheval et al., 2020)
Review of environmental challenges and pandemic crisis of Covid-19	Aims to investigate the environmental challenges caused by the SARS-CoV-2 pandemic crisis	Water pollution, increasing chemical pollution in the air, and increasing the production of non-biodegradable waste were the most detrimental effects of COVID-19 on the environment. Home quarantine is associated with positive achievement, which is the reduction in waste production and protection of the environment	Poursadeqiyan et al. (2020)
Indirect impact of COVID-19 on environment: A brief study in Indian context	To provide evidence-based insight into improvement of air quality and environment during pre and post -lockdown of this pandemic situation	Reduction in air pollution after the COVID-19 outbreak has been reported Rigorous study on the effect of the implementation of short-term lockdown as an alternative measure for pollution reduction and its effect on the economy is needed	(Lokhandwala and Gautam, 2020)
Risks of Covid-19 face masks to wildlife: Present and future research needs	To provide a critical review of COVID-19 face mask occurrence in diverse environments and their adverse physiological and ecotoxicological effects on wildlife To discuss the potential ecotoxicological effects imposed by the released particles and leached hazardous chemicals recently reported for such items	Thousands of COVID-19 disposable Masks may enter the environment daily Wildlife interactions with disposable masks have been reported in several countries Disposable masks release contaminants with the potential for ecotoxicological effects Monitoring and ecotoxicological studies should be prioritized Mitigation measures should be implemented to control plastic pollution	(Patrício Silva et al., 2021)
Coronavirus in water media: Analysis, fate, disinfection and epidemiological applications	To examine the possible transmission of SARS-CoV-2 via water media, the fate of coronaviruses (CoVs) in water systems	Detection of the virus in water media provides a potentially powerful tool for quantitative microbiological risk assessment (QMRA) and wastewater-based epidemiology (WBE) Challenges and critical issues relevant to the detection of coronaviruses in water matrixes with both direct and surrogate methods as well as in the implementation of epidemiological tools are there	(Buonerba et al., 2021)
SARS-CoV-2 in the environment—Non-droplet spreading routes	To summarize current knowledge on the SARS-CoV-2 transmission and elucidate the viral survival in the environment, with particular emphasis on the possibility of non-droplet transmission	SARS-CoV-2 may spread via a non-aerogenic route via surfaces and sewage Sewage can be a source of SARS-CoV-2 in soil Municipal waste from people infected with SARS-CoV-2 or people in contact with patients with COVID-19 may be a hazard It is imperative to distinguish the detection of viral RNA from the detection of complete virions	(Wiktorczyk-Kapischke et al., 2021)

(2020) found that fecal analysis of the 73 SARS-CoV-2 infected hospitalized patients showed that stool samples of 39 patients tested positive for the virus, and the samples of 23.29% remained positive even after the presence of the viral RNA in the respiratory tract reduced to an undetectable level. A study by Tang et al. (2020) has reported the detection of SARS-CoV-2 in stool samples of an asymptomatic child who tested negative for SARS-CoV-2 in respiratory tract specimens. The viral count detected in the infected individuals'fecal matter genome ranges from 600,000 (Zhang et al., 2020c) to 30,000,000 per mL (Woelfel et al., 2020). The practice of open defecation or pit latrines used by approximately 900 million people worldwide in low-income countries could potentially exacerbate the pandemic (WHO and UNICEF 2017). In pandemic situations, this becomes a huge problem, due to the direct disposal of fecal matter or runoff into water bodies used by the community for general purposes. The existence of the virus in human excreta does not signify the virus's infectivity since these may not be in the viable state in each case.

Other than stool samples, SARS-CoV-2 is also detected in sputum, saliva, and other clinical samples, which are subsequently released into the hospital wastewater, and conveyed through the municipal sewer system to WWTP (To et al., 2020; Wang et al., 2020b). Existing water infrastructure connected with hospitals, public places, residential areas, toilets, drains, runoffs, and water treatment plants creates the opportunity to transmit the virus within a large area. SARS-CoV-2 RNAs have

been detected in treated and untreated wastewater with up to 10^5 copies per liter (Wu et al., 2020a; Wurtzer et al., 2020). Widespread leakage in sewage networks and septic tanks, specially with older infrastructure, poses an additional risk of exposure to SARS-CoV-2. Storm events can raise the chance of SARS-CoV distribution due to sewer overflows (Bogler et al., 2020). Thus, global efforts should be made to improve sanitation through proper operation and maintenance of sewer systems to prevent viral contamination of the aquatic environment. The number of infections in a community could potentially increase if the community shares sewer systems. Luo et al. (2020) studied the spread of SARS-CoV-2 in a public bath center in China and observed a cluster transmission of the virus among eight people who shared the same bath center.

Even though several studies have confirmed the presence of SARS-CoV-2 in water, wastewater, soil, and food, the transmission of the virus through different environmental routes is yet to be clarified. For example, transmission routes of SARS-CoV-1 in an apartment complex revealed the possibility of SARS-CoV-1 transmission via aerosolized wastewater (McKinney et al., 2006). This study suggested that viral aerosols created by toilet flushing or faulty plumbing systems have been drawn into the apartment through bathroom floor drains where the initial exposures occurred. In 2003, in a housing block in Hong Kong, 342 SARS cases were reported, with 42 deaths. The airborne transmission of SARS-CoV via interconnected wastewater plumbing systems within the building was identified as the root cause of the super-spreading of the virus (WHO, 2003). Two studies by Pasalari et al. (2019) and De Graaf et al. (2017) also reported the transmission of rotavirus and norovirus through aerosolization during wastewater and sludge treatment and handling. A similar hypothesis can be used to understand the alternative pathways of SARS-CoV-2 transmission in a water-soil-food environment. Therefore, the public health risk associated with aerosolizing of SARS-CoV-2 contaminated wastewater and subsequent inhalation of infectious bio-aerosols require further investigations.

SARS-CoV-2 transmission through the soil compartment has not received as much attention as for water and air; there is an urgent need to study the role of soil in the secondary transmission of SARS-CoV-2. Further, storm-water runoffs from these agricultural lands may eventually end up in groundwater or surface water bodies. Viruses are highly mobile in the subsurface due to the stearic interactions with porous media employing outer spike glycoproteins (Bhattacharjee et al., 2002; Gutierrez and Nguyen, 2013). Enteric viruses have a size ranging between 25 and 100 nm, potentially allowing them to infiltrate the aquifers more quickly than larger bacteria or protozoa (Borchardt et al., 2003). Viruses released through untreated sewage may contaminate the aquifer system, especially with high infiltration rates (30 and 110 m/yr) (Marsalek et al., 2008). The continued release of contaminated sewage affects the soil ecosystem and could work as the sink of SARS-CoV-2 for other sources involved in secondary viral transmission. Therefore, the interaction with various environmental matrices - air, water, soil, and food should be thoroughly studied to understand the transmission of SARS-CoV-2 better. Fig. 1 illustrates the potential pathways of the novel coronavirus in the water and soil environment.

2.1.2. SARS-CoV-2 persistence or presence in water and wastewater

The COVID-19 pandemic ravaged developed and developing countries equally, with the United States and India sharing the highest virus case-load. When controlling the contagion, a common theme across many countries is a lack of resources and inadequate infrastructure to test a large population to manage or mitigate the spread of the virus even when a significant number of people (40%) are already infected with the virus (Esakandari et al., 2020, WHO and UNICEF 2020). Several challenges exist to estimating viral infection cases accurately due to multiple limitations, including lack of uniformity in standard protocol for laboratory testing, test duration, high signal-to-noise ratio, and variations in sample collection, storage, and transport. Additionally, the infected person remains asymptomatic for two weeks from the day of the exposure – a critical window for quarantine/intervention and contact tracing (Esakandari et al., 2020; Peccia et al., 2020). While some countries have expanded testing for the virus to symptomatic and asymptomatic persons, challenges such as the cost of the test, test administration, and dissemination of results still exist. For example, suppose the test is administered before the person becomes symptomatic (lag time due to the delayed onset of symptoms). In that case, the test results might be negative or inconclusive due to the low virus load in the sample (Rubin, 2020). Given these challenges, monitoring water and wastewater sources to determine the occurrence and the likelihood of community transmission of SARS-CoV-2 appears to be a promising alternative. Because testing and analysis of wastewater samples will provide a 12 to 16-day advanced notice before the onset of the disease. Environmental surveillance can be effectively used to mitigate the future onset of disease.

A perusal of the literature shows that environmental surveillance is a proven strategy for combating diseases associated with the ingestion of

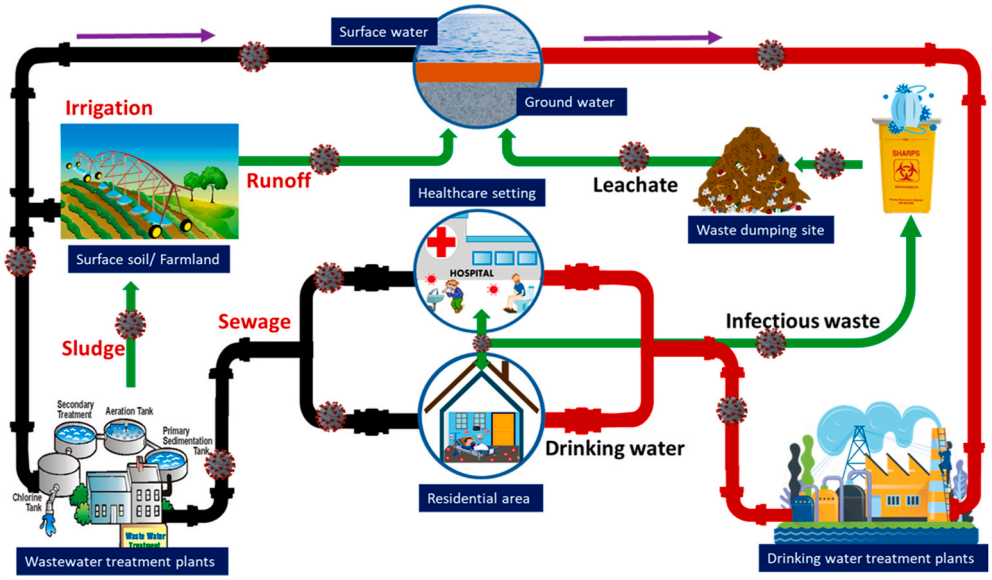

Fig. 1. Possible transmission routes of SARS-CoV-2 in water and soil environment.

contaminated water. The earliest historical example of such surveillance is the 1849 epidemiological study by Dr. John Snow. He demonstrated the incidence of cholera and typhoid cases to the source of contaminated drinking water (Tulchinsky, 2018). Even today, many urban cities with centralized wastewater treatment facilities often utilize monitoring data to control the onset of waterborne illnesses (Crittenden et al., 2012). Such surveillance is currently used to track polio outbreaks and the growth of antimicrobial-resistant microorganisms (WHO, 2020a). Some recent studies have successfully demonstrated a correlation between SARS-CoV-2 ribonucleic acid (RNA) present in an infected individual's stool or upper respiratory sputum and similar detection in the wastewater sample (Peccia et al., 2020; Westhaus et al., 2021).

Monitoring water and wastewater sources for the occurrence and persistence of the SARS-CoV-2 virus is a financially intensive endeavor yet a necessary and critical area of research to mitigate the spread of the virus. Uniform protocol and standardized procedure for detecting SARS-CoV-2 virus in water/wastewater samples could be quickly developed. There is a better possibility of developing a universal protocol for standardized sample collection and analysis (using dedicated analytical instruments) to generate credible data on the occurrence of the virus in water samples. Wastewater-based epidemiological studies with the well-established protocols for testing viruses using a polymerase chain reaction (PCR) already exist (WHO, 2020a). Recent studies have demonstrated that sequencing of the SARS-CoV-2 virus released through the wastewater by infected patients correlates well with the subsequent increase in community transmission and rise in documented clinical cases of SARS-CoV-2 (Bivins et al., 2020; Medema et al., 2020). Real-time tracking of infection cases in urban and rural areas will be possible at the centralized wastewater collection systems.

To better track the infection cases, it is necessary to understand the occurrence and persistence of the SARS-CoV-2 virus. A knowledge gap exists between the release of virus load by an impacted person and the fate and potential inactivation of the virus in the presence of wastewater. Most of the studies are based on computer-simulated models to understand the persistence of the virus in the post-release scenario. A direct evidence-based study showed the persistence of the SARS-CoV-2 virus in wastewater (Medema et al., 2020). The authors demonstrated that the magnitude of detection of virus RNA in wastewater samples corresponds with the magnitude of virus infection. It means that wastewater surveillance could effectively mitigate widespread infection during incubation (Medema et al., 2020). While it is unlikely that the wastewater will serve as a critical exposure pathway for SARS-COV-2, the increased virus load in the wastewater could portend the onset of community transmission (WHO, 2020c).

2.1.3. SARS-CoV-2 persistence in soil

Soil health is vital for maintaining plant, animal, and human health. Soil comprises of billions of microorganisms including pathogens that act as the reservoir for life on earth. These pathogens are called soil-transmitted pathogens, which exist in soil for a long time before infecting the host using soil particles as vectors (Amoah et al., 2017). Duboise et al. (1976) reported that human entero-viruses could remain viable in the soil for 100 days. Compared to extensive studies on the persistence and transmission of SARS-CoV-2 in water, very few studies documented the persistence in the soil environment. The soil compartment of the environment acts as the destination for most contaminants, including solid waste, sewage from WWTPs, bio-solids from landfills, and atmospheric particle fallouts. Studies on the persistence and transmission of sewage sludge-borne pathogenic organisms in soil suggested that the application of sewage on soil could increase the survival and transport of pathogens including adenoviruses in soil due to high organic matter content in bio-solids (Horswell et al., 2010). In addition, a study by Pourcher et al. (2007) who discovered the potential for contamination of soil and water by entero-viruses due to land spreading of municipal sewage sludge, estimated that the entero-viruses could survive up to 14 days in soil. Leachate generated from laboratory-treated sludge also has shown the existence of *Escherichia coli* bacteria which was viable for four weeks in leachate (Pousada-Ferradás et al., 2012).

Similar findings have reported the presence of SARS-CoV-2 in sewage sludge, further providing evidence for the potential soil contamination by SARS-CoV-2. Recently Peccia et al. (2020) documented the occurrence of SARS-CoV-2 load in primary sludge from municipal WWTPs in a metropolitan area of New Haven, USA. Traces of SARS-CoV-2 in primary and waste-activated sludge from 9 WWTPs in Istanbul (Kocamemi et al., 2020). Wastewater sludge treatment processes are inadequate to eliminate SARS-CoV-2 because SARS-CoV-2 was detected in treated and untreated sludge, suggesting that only thermal hydrolysis could destroy the virus in sludge (Serra-Compte et al., 2021). The higher affinity of the virus towards sludge is attributed to the presence of organic matter in sludge and the inherent hydrophobicity of the virus (Conde-Cid et al., 2021). In places where SARS-CoV-2 contaminated sewage is used as a soil organic amendment, soil and crop plants may be exposed to the virus, which in turn may lead to contamination of food materials (Núñez-Delgado, 2020). Direct discharge of disinfected solid wastes, including medical and domestic wastes, land application of untreated wastewater as a secondary source of irrigation, and application of sewage as a soil amendment promotes soil contamination of SARS-CoV-2. Foods grown on such contaminated soils may enter the human food chain through potential uptake by crop plants (Anand et al., 2021b). Hence, a substantial screening should be conducted on the wastewater effluents and sewage sludge before their application in soils to prevent COVID-19 migration to other environmental compartments.

Strong evidence of the transmission of the virus through the soil-food route and its human infectivity is lacking. The possibility of the virus being deactivated and becoming non-infective during human food consumption cannot be ignored.

In regions with no streams or rivers located near the WWTPs or if no wastewater treatment facilities exist, wastewater is often directly disposed of on barren land in such a scenario. Zhang et al. (2021) documented the presence of SARS-CoV-2 in outdoor hospital environments up to a count of 205–550 copies/g of SARS-CoV-2 in the soil in locations near the hospital and wastewater treatment facilities. The authors detected SARS-CoV-2 in the soil samples within 2 m from the adjacent of wastewater treatment tanks. These results suggest that outdoor hospital environments need to be considered high-risk areas since they have reported a significant viral RNA load which could act as a secondary transmission route.

Further, increased use of personal protective equipment, including face masks, gloves, and other medical wastes, and their disposal on land without proper decontamination creates a chance for SARS-CoV-2 migration to the soil. The persistence of viable SARS-CoV-2 viruses on solid waste surfaces may further increase the risk of soil contamination of SARS-CoV-2 (Ilyas et al., 2020). Existing studies have proved that SARS-CoV-2 can survive for more than ten weeks in soil compartments under suitable conditions (Li et al., 2020). Similar to SARS-CoV-2 detection in wastewater as an epidemiological tool to inform future risks, quantifying SARS-CoV-2 in soil could also help identify future risks of viral transmission.

2.1.4. Detection and identification of coronavirus in wastewater/soil

Detection and identification of SARS-COV-2 are accomplished through genome sequencing of the virus through direct metagenomic sequencing, PCR amplicon sequencing, and target enrichment sequencing (Charre et al., 2020). Sequencing the genome is time-consuming, but developing a unique primer set takes little time once it is identified. Often, multiple sets of primers are tested to minimize the time needed to identify the definitive primary set that can be used for environmental surveillance. These methods share common fundamental principles that govern PCR. They operate on the principles of enzyme-based ligation and amplification. Direct metagenomic sequencing using next-generation sequencing would be appropriate for the SARS-CoV-2 virus (Subbaraman, 2020; Wu et al., 2020b), while the

other two methods can be employed to detect the mutations of the existing virus. Environmental surveillance is ideally suited for large-scale wastewater treatment plants with centralized wastewater treatment collection facilities. As such, surveillance for SARS-CoV-2 is still in the developing stage. Nonetheless, this approach has already been implemented to identify community virus transmission in developing countries. For example, countries that lack the resources to develop a rapid and robust testing protocol for the virus were worst hit during the early days of the pandemic. Detection and identification of SARS-CoV-2 in wastewater using PCR sequencing are fast and reliable, which has tremendous implications for human health. At present, it is necessary to establish a uniform operational procedure for accurate detection and quantitation of SARS-CoV-2.

2.1.5. Fate and potential transmission of SARS-CoV-2 in wastewater and soil

SARS-CoV-2 belongs to the group of enveloped viruses as it contains a lipid membrane enclosing the capsid protein (Castaño et al., 2021). The fate of viruses in different environmental compartments is determined by the presence or absence of an envelope. Enveloped viruses have shown higher survivability in fecal matter and aquatic environments than non-enveloped viruses due to their sensitivity toward temperature, pH, disinfectants, and other solvents (Kumar et al., 2020; La Rosa et al., 2020). In cases where the surface S-proteins in the virus are preserved even if extreme environmental conditions change the virus envelope, the enveloped viruses could survive for a long time in a viable state. For example, COVID viruses such as HCoV have reportedly survived for ten and five days in primary and secondary sewage respectively (Gundy et al., 2009). Compared to other enveloped viruses, this unusual behavior of CoVs has brought the current COVID-19 situation to a challenging global pandemic.

Many factors, such as temperature, pH, organic matter, suspended particles, chemical, and biological aggregates, and the existence of microorganisms can influence the survival of SARS-CoV-2 in water and soil (Gundy et al., 2009; La Rosa et al., 2020). In the supplementary materials, the fate and possible transmission of SARS-CoV-2 in water and soil are discussed in detail (SI, Section S1).

3. Environmental challenges

3.1. Water

Access to clean water and proper sanitation has remained a significant concern, especially for people in developing countries. People living in slums, refugee camps, and peri-urban areas face a daunting challenge due to the lack of clean water for drinking purposes and proper hygienic practices (WHO and UNICEF 2017). COVID-19 presents challenges from the perspectives of both water quality and water quantity. Implementing simple but efficient protective measures such as proper hand-washing with clean water and soap has increased the demand for clean water among the public where it is least prioritized, and the WASH sector is underfunded in low-income countries (Amuakwa--Mensah et al., 2021). Even before the pandemic (2017) nine out of 10 of the 785 million people who lived in sub-Saharan Africa (400 million), Eastern and South-Eastern Asia (161 million), and Central and South Asia (145 million) were reported to have limited clean water sources and were utilizing un-improved sources of surface water (Donde et al., 2021). In this context, external development assistance is required to improve the WASH conditions during this critical situation mainly in low-income and middle-income countries.

Fewer studies have reported water quality improvement during lockdown periods due to the shutdown of industrial activities that released wastewater to surface water bodies (Yunus et al., 2020). However, some additional challenges have emerged with the generation of more healthcare wastes and personal protective equipment and their direct discharge into water bodies during the COVID-19 pandemic than usual (Bondaroff and Cooke, 2020). It will be an environmental issue to bury infected dead bodies in unsanitary conditions. In some regions, high groundwater levels can cause pollution due to unsanitary burial (Poursadeqiyan et al., 2020). This further indicated that the provision of proper WASH services is challenging in situations where water is contaminated with SARS-CoV-2 due to inadequate management of waste.

3.1.1. Hand washing

Even though the WHO recommends frequent washing of hands with soap under running water for at least 20 s to control the current COVID-19 pandemic (WHO, 2020a), this leads to additional challenges due to excessive use of soap and water. A broad discussion on the environmental concerns of hand washing is provided in the supplementary materials (SI, Section S2).

3.1.2. Contamination and epidemiological risk

As discussed in previous sections, improper disposal of infectious waste has led to SARS-CoV-2 contamination of wastewater alarming their significant role in spreading the disease to other people (Yeo et al., 2020; Yuan et al., 2021). This brings the need for special guidelines for disinfection and decontamination of wastewater to destroy and eliminate the virus. Discharge of wastewater containing potentially infectious SARS-CoV-2 may result in pollution of surface water and groundwater affecting the quality of water resources (Bivins et al., 2020). However, many aspects remain unresolved regarding infectious SARS-CoV-2 transmission through wastewater. The survival of the virus in wastewater depends on different environmental factors and types of water (La Rosa et al., 2020). Despite the existence of SARS-CoV-2 RNA in raw wastewater, no infectious virus has been isolated from the same samples, implying that viral RNA detection misjudged the risk of infection (Rimoldi et al., 2020). Technical constraints that occur in culturing SARS-CoV-2 on cell culture from such samples may be the reason for this consequence. Whether or not these research works lead to epidemiological conclusions based on practical applications, the fact remains that the novel coronavirus or its fragments have already been detected in many water systems.

3.2. Effect of chemical use

Massive research activities have been globally realized to develop suitable therapies and vaccines for COVID-19, caused by SARS-CoV-2 (Anand et al., 2021c; Anand et al., 2021d). SARS-CoV-2 shows good stability, at room temperature, and a broad range of pH values (pH 3–10) (Chin et al., 2020). As discussed previously, SARS-CoV-2 can persist in a favourable environment (for example on surfaces of different objects that are commonly used) for several days, and it was found to persist also in sewage and wastewater (Anand et al. 2021a, 2022a). In this frame, disinfection has been recognized as a fundamental measure to directly combat the virus and prevent its spread (Anand et al., 2022a; Iyer et al., 2021).

Moreover, SARS-CoV-2 was found to be susceptible to several disinfectant typologies. Some agencies such as European Center for Disease Prevention and Control (ECDC) have proposed lists of effective disinfectants and developed guidelines and protocols for the suitable use and application of these chemicals in different settings (healthcare and non-healthcare areas), to assure their validity. Almost all the proposed products are composed of surfactants, soap, and oil, with different active ingredients (ECDC, 2020). The main active ingredient used is quaternary ammonium, while others are obtained by also making mixtures of sodium hypochlorite, ethanol, isopropanol, hydrogen peroxide, peroxyacetic acid, and hypochlorous acid. Fig. 2 shows the suggested contact times, divided into quartiles, for registered EPA disinfectants, reported as a function of the active ingredients.

However, many disinfectants, which are employed for surface decontamination, show high toxicity and can generate environmental

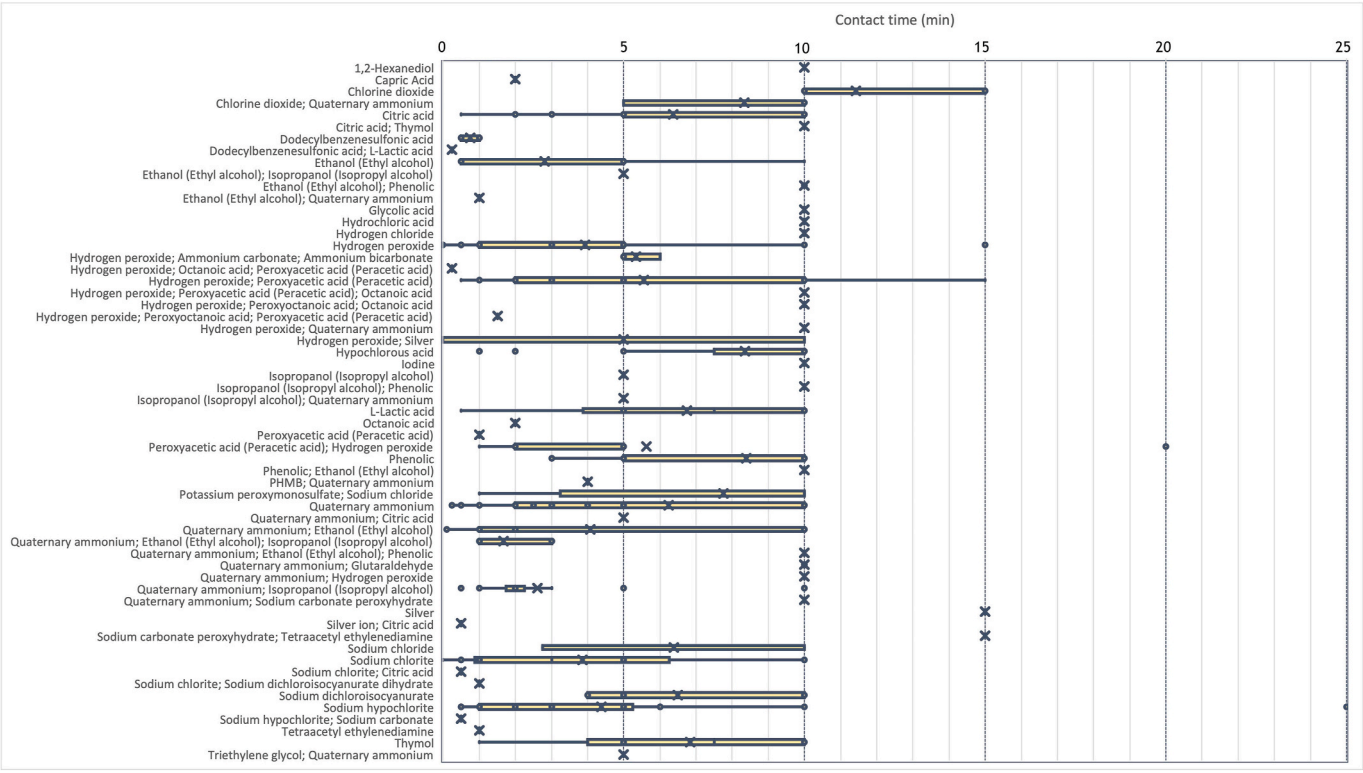

Fig. 2. Statistical distribution (representing the median and quartiles) of contact time (in a minute) suggested by companies proposing the registered EPA products (data source (USEPA 2020)). This analysis is made based on active ingredients (used in COVID-19 disinfectants).

contamination. Then, great attention was also devoted to reducing the possible negative effects of these substances, by suggesting the suitable amount/concentration of all the chemicals used for decontamination, assuring that they are employed at their minimum necessary amount (Sarada et al., 2020).

However, the massive release of SARS-CoV-2 disinfectants in the environment (due to inappropriate strategies to manage the wastes derived) is alarming due to the potential adverse effects that are not completely known.

3.2.1. *Environmental cleaning and disinfection procedures*

A disinfection procedure is based on the use of substances able to remove pathogenic microorganisms. It is generally formulated to destroy and/or inactivate microorganisms. The user agents can be categorized into various classes, depending on their chemical nature, for example, alcohols, halogens, acids, alkalis, phenols, oxidizing agents, biguanides, quaternary ammonium compounds, and aldehydes (Dhama et al., 2021).

The disinfection efficacy relates to the properties of the disinfectants or sanitizers, but it is also dependent on the virus characteristics, the environment where the pathogen is present, or where the disinfection must be realized.

On the other hand, the environmental cleaning process aims to remove the virus mechanically and/or chemically. Indeed, successful inactivation of SARS-CoV-2 has been obtained also by using several detergent products that can be able, for example, to affect its lipid membrane (Dhama et al., 2021).

Moreover, to limit the pandemic spread, the products used for environmental cleaning and/or disinfection must be highly effective to remove the virus. Despite that literature (Shimabukuro et al., 2020) has shown that several detergents are also effective in SARS-CoV-2 inactivation, it is suggested to realize cleaning coupled with disinfection to obtain more significant reductions of the microbial load. The Center for Disease Control (CDC) has published guidelines for environmental cleaning in healthcare and non-healthcare settings (ECDC, 2020), strongly suggesting the use of protocols to guide the cleaning of the environment and equipment.

3.2.2. *Chemical waste disposal effects*

In the last two years, the use of some pharmaceuticals and disinfectants has rapidly grown due to the ongoing pandemic (Subpiramaniyam, 2021). While the attention to the chemicals devoted to reducing the SARS-CoV-2 spread is a wide-investigated scientific research area, the potential negative effects of these products are still not considered at the same level. Indeed, there is less information about the possible environmental consequences of several antiviral drugs and/or disinfectants used for SARS-CoV-2 treatment. The increased consumption of chemicals inevitably results in the occurrence of high residual levels of contaminants in the environment, with alarming potential and unknown effects on non-target species (Subpiramaniyam, 2021).

The pharmaceuticals (or their metabolites) quantities in the environment are dependent on the percentage of the treated people, which increases exponentially during pandemics. Moreover, the pandemic has exacerbated not only the use of some pharmaceuticals (for example in the hospital) but also the general use of disinfectants. These substances show several advantages in terms of simplicity of application, diffusion, cost, and range of usage on almost all objects' surfaces.

The toxicity of some substances and/or surface detergents is well-documented in the literature. For example, chlorine-based disinfectants may damage proteins and destruct the cell walls of aquatic wildlife and plants (Zhang et al., 2020b), and bond with dissolved organic matter in surface water to produce some harmful by-products (like trihalomethanes and haloacetic acids) (Guo et al., 2021). These by-products can also affect the activity of microorganisms that are supposed to remove pollutants in WWTPs. Some disinfection by-products have been already classified as carcinogens: this is for example the case of chloramine and N-nitrosodimethylamine, which are derived from nitrogen combination with some disinfectants (Guo et al.,

2021).

In several other cases, the use of disinfectants can have effects that are still poorly investigated. For example, it was reported that a large number of wild animals died near Wuhan, probably due to the effects of the use of large quantities of outdoor disinfectants (Nabi et al., 2020).

Literature also reports that the effects of the disinfectant on non-target species are still almost unknown; however, there is the first evidence that some chemicals can induce hormesis with a reported significant response at doses smaller than the traditional toxicological threshold (Agathokleous et al., 2022).

In this frame, it has also emerged that not only toxicity but also antimicrobial resistance is a very dangerous effect caused by excessive chemical use (Singh, 2020). In particular, due to the biocidal characteristics of disinfectants, their excessive use is associated with an increase in antimicrobial resistance (Pérez de la Lastra et al., 2022). It is reported that exposure to 0.0004% phenolic disinfectant triclosan increases the risk to develop bacterial resistance and cross-resistance in *Staphylococcus aureus* and *Escherichia coli* (Wesgate et al., 2016). It is also known that disinfectants based on chlorine and calcium hypochlorite, generally used for drinking water disinfection produces bacterial resistance (Mohammed, 2019). Special attention must be devoted to the disinfectants used in hospitals. The use of hand disinfectants based on alcohol is responsible for the emerging alcohol-tolerant *Enterococcus faecium* (Wang et al., 2021).

Finally, concerning the possible toxicity of disinfectants, it is important to highlight that, as documented in Wuhan, the excessive use of disinfectants not only can cause water and soil pollution but also concerns about pollutants airborne transport and consequent adverse effects of these substances (Anand et al., 2021b). This problem is not only relegated to the use of outdoor products but also household disinfectants. Indeed, a recent paper reporting data about poisoning accidents due to the exposure to disinfectants during pandemics (Soave et al., 2021), shows that the highest increase of incidents, in comparison to previous years, was observed for the inhalation cases during pandemics (+122% in 2020 in comparison to 2019). Indeed, apart from the utilization of sprays, chemicals used on the surface can be inhaled or become airborne, also contributing to reducing the quality of indoor air. Great attention must be also done to improper disinfectant mixing before use, which can also generate hazardous/toxic gases (Rai et al., 2020).

These considerations based on literature analysis, show that because COVID-19 spread around the world, the massive use of disinfectants may cause a secondary disaster, not only for human health but also for the environment. Then, the more suitable ways to use and dispose of these products must be proposed based on their toxicity, which is still not completely known for several of these chemicals. In this frame, it is evident that several works must be still done in this context.

In the last years, growing attention appeared in the literature concerning emerging pollutants. They are, for example, pharmaceutical residues, that are hard to remove in common WWTPs with a consequent possible diffusion of these contaminants in the environment (Fahimi et al., 2020).

Considering the similarities between disinfectants and pharmaceuticals, which are based on their use, entry into the environment and pathways, regulations, environmental risks, and so on, the first activities that are proposed for these emerging pollutants may be also devoted to disinfectants.

The idea is to use a starting evaluation point and to adapt it in view of the proposal of the most suitable prevention strategies and environmental safety evaluations. For this aim eco-pharmacovigilance (EPV), which has been proposed as a new strategy for the detection, evaluation, and understanding of possible adverse effects of pharmaceuticals in the environment (Wang et al., 2021), may be suggested to be used also for disinfectants. Eco-friendly cleaning and disinfecting, such as EPV, can aim to control disinfectants sources and related human behaviors to constrain the discharge of these substances in the environment (for example by sewage entering rivers and lakes); thus, it may be a feasible solution for the limitation of disinfectants pollution. However, it is very important to stress that great attention must be devoted also to air transmission of disinfectants, which is not in general, a considered way of spreading pharmaceuticals in EPV. Fig. 3 reports the dimensions of the proposed eco-friendly cleaning and disinfecting strategies.

3.3. Waste

The ongoing COVID-19 pandemic has compelled people to consume massive amounts of personal protective equipment (PPE) worldwide. Among them, the use of face masks, face shields, and gloves has tremendously increased as an efficient way to prevent the transmission of the virus (Torres and De-la-Torre, 2021). As most of these PPEs contain plastics or other derivatives of plastics, extensive usage generates an enormous amount of waste released to the environment in a short period. In this segment, the impact of that waste burden on the environment is discussed by categorizing them broadly into single-use mask waste, waste generated from hospitals, and general plastic waste, including face shields, gloves, etc.

3.3.1. Impact of solid waste on the environment (mask waste)

Face masks help prevent the spread of coronavirus and other diseases; ever since the COVID-19 outbreak began, the production and usage of face masks significantly increased. Most governments worldwide made it obligatory to wear face masks in public places to control the pandemic. A recent study by Prata et al. (2020) showed that an astounding 129 billion face masks are estimated to be used globally every month, and most of these are disposable face masks made from plastic microfibers. According to a study conducted by World Health Organization (WHO), 89 million medical masks will be required for the USA alone to battle against COVID-19, while the plastic innovation hub has identified that the domestic demand for masks in the U.K. is around 24 billion per year (Selvaranjan et al., 2021). Moreover, the Japanese Ministry of Economy, Trade, and Industry noted that more than 600 million face masks were required for April 2020 (Fadare and Okoffo, 2020b), while Boroujeni et al. (2021) estimated the daily face mask use in Victoria, Australia as 5 million masks per day during this COVID 19 pandemic. Further, China, the most prominent face mask manufacturer globally, has raised its daily production of medical masks to 15 million as of February 2020.

Face masks can be of different types, such as N95, surgical masks, and fabric/cloth masks. The most commonly used disposable surgical masks are made of three layers. The outer layer is made up of nonabsorbent material like polyester, which protects against liquid splashes. The middle layer is composed of non-woven fabrics such as polypropylene and polystyrene, which are created using a melt-blowing process, thus preventing droplets and aerosols via an electrostatic effect. Finally, the inner layer is absorbent material like cotton to absorb moisture (Rossettie et al., 2020). On the contrary, N95 consists of four layers, where the first layer is spun-bond polypropylene while the second, third, and fourth layers are composed of cellulose/polyester, melt-blown polypropylene filter material spun-bound polypropylene, respectively. Different polymers are used in manufacturing masks, and fabric polypropylene, a commonly produced plastic globally, is used the most (Dhivyadharshini et al., 2020).

Most surgical masks are disposed of after a single use and end up in street landfills even in the freshwater and marine environments by surface run-off, river flows, oceanic currents, wind, and animals (via entanglement or ingestion), thus polluting rivers and oceans (Xu and Ren, 2021). Waste masks have been increasingly reported in different environments, and social media have shared photographic evidence of fish entrapment and bird entanglement in elastic straps of masks and ingestion by urban and domestic animals. Additionally, similar to other plastic debris, disposable masks may accumulate and release harmful chemical and biological substances, such as bisphenol A, heavy metals,

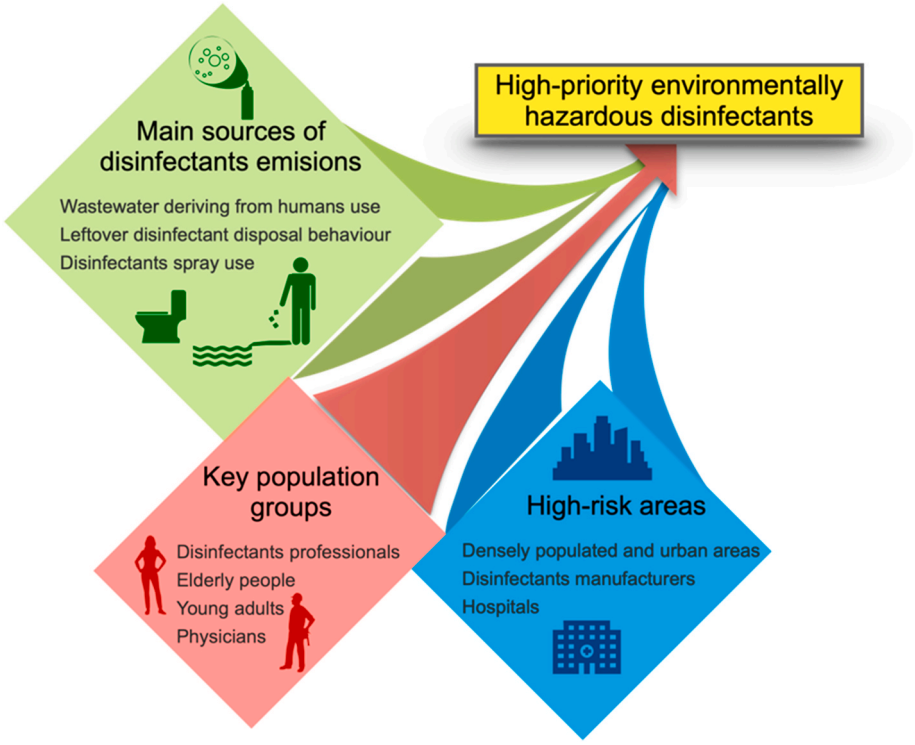

Fig. 3. Dimensions of the proposed eco-friendly cleaning and disinfecting strategies.

and pathogenic microorganisms (Xu and Ren, 2021). Furthermore, adverse health effects are known to cause the uptake of microplastics released by facemasks. However, there are no specific waste mask collection methods in many parts of the world, especially in Asia (Selvaranjan et al., 2021). Sometimes, masks in the trash are treated as 'general waste,' which means most of the used masks end up in cities' landfill aquatic systems, and sometimes they are often incinerated along with other medical waste. Recently, scholars found that 1.6 million face masks entered the oceans in 2020 (Bondaroff and Cooke, 2020), which indeed could cause long-term effects on the marine environment (De-la-Torre and Aragaw, 2021; Fadare and Okoffo, 2020b). Therefore, with increasing reports on inappropriate disposal of masks, it is urgent to recognize this potential environmental threat where millions of tons of plastic waste are released into the environment within a short period. Some examples of a range of environmental challenges are shown in Table 2.

This indicates that improper disposal of face masks during the ongoing pandemic increases environmental pollution and negatively impacts human and animal health. Therefore, sustainable solutions need to reduce the environmental impacts while meeting the mask demand.

3.3.2. *Hospital solid waste on the environment*

With the outbreak of coronavirus disease, the generation of medical waste has rapidly increased in almost every part of the world, especially in hospitals, clinics, laboratories, quarantine centers, and research centers. Thus, hospital waste can be identified as one of the significant medical wastes, including different types of infectious, sharp, pharmaceutical, pathological, genotoxic, and radioactive waste (Aghapour et al., 2013). However, the lack of procedures and technologies to manage healthcare waste in many hospitals releases more persistent organic pollutants into the environment (Maalouf and Maalouf, 2021).

In addition, researchers found that the COVID-19 epidemic increases 102.2% of waste generation in private and public hospitals (Kalantary et al., 2021). For instance, in Wuhan, medical waste generation gradually increased from the usual level of 40 tons per day to a maximum of 240 tons per day (Maalouf and Maalouf, 2021). In addition, United Nations Environment Programme (UNEP) reveals that healthcare waste generation due to the COVID-19 pandemic can be found as 3.4 kg per person per day and 2.5 kg per bed per day in developed and developing nations, respectively (Tsukiji et al., 2020).

Table 2
Environmental Challenges associated with solid waste management.

Challenge	Consequences/Description	Reference
CO_2 emission and global warming	N95 masks create 50 g CO_2-eq emission per single mask, excluding the transportation process The surgical mask creates 59 g CO_2-eq per single mask Cloth mask creates 60 g CO_2-eq greenhouse gas emission per single mask	Klemeš et al. (2020)
Threats to Wildlife	In Columbia, birds are tangled in discarded COVID masks in trees and die after a few days because of masks wrapping their bodies. When some animals use masks as a food source, eventually, those end up in their stomach and cause deaths.	(Boyle, 2020)
Threats to aquatic life	Waste and masks end up in fresh/seawater bodies, are toxic to marine life, destroy their process, and cause impaired reproduction, growth, and death.	(Yang et al., 2020)
Improper solid waste handling	Hospital mixed waste is sent to incineration and disposed of in a landfill. Thus, remaining plastics in masks create adverse environmental impacts since most of them are resistant to corrosion, hard to decompose by microorganisms, and ultimately pose soil and water pollution.	(Webb et al., 2015)
Adsorb persistent organic pollutants (POP)s and heavy metals	Enter major food web due to bioaccumulation of the POP and heavy metal in aquatic animals	Haque et al. (2021)

3.3.3. Plastic waste

Plastic materials have become an essential part of the modern population. The demand and manufacturing of plastic products have increased gradually since their mass production (Geyer et al., 2017). Poor solid waste management or incorrect disposal make plastic waste a global environmental concern (DellaSala and Goldstein, 2017). Plastic waste undergoes physical changes such as size and shape upon interaction with the environment, thus leading to detrimental effects on organisms (Cole et al., 2011). Moreover, these waste matters persist in the environment for long periods due to their low biodegradability (Andrady, 2017).

The COVID-19 pandemic creates plastics (gloves, face shields, sanitizer bottles, cans, face masks) as the primary protection material to sustain health care and public health. Unfortunately, plastic waste treatment and recycling rates have not been practiced as the pandemic continues (Parashar and Hait, 2021). Recently, it has been estimated that more than 8 million tons of waste are associated with pandemic activities, and these rates will increase daily. Accordingly, more than 25, 000 tons of waste will end up in the water bodies based on the investigated results from 193 countries (Peng et al., 2021). According to the number of COVID-19 patients, scholars found almost 87% of excess waste was generated from hospitals, and individuals contributed 8% of total excess waste. In addition, lockdown, social distance, and isolation lead to an increase in the rate of online shopping, and ultimately, this contributes to the rise of the use of packaging materials that usually contain plastic derivatives (Thakur, 2020).

Single-use face masks have been identified as a leading source of microplastic pollution globally (Fadare and Okoffo, 2020a). When masks are disposed to the environment, it is subjected to solar radiation and heat. However, the degradation of polypropylene is retarded due to some of its resistant properties, such as high hydrophobicity, high molecular weight, lacking an active functional group, and a continuous chain of repetitive methylene units. This leads to the persistence and accumulation of polypropylene in the environment. Further, in-situ weathering results in a large number of micro-sized polypropylene particles (<5 mm) during a relatively short period (weeks) and further fragmentation into nanoplastics (<1 mm) (Mattsson et al., 2018).

Furthermore, scientists debate that around 29% of pandemic-associated plastic waste will end up on the seabed and almost 71% of waste on beaches at the end of this century. However, the total amount of pandemic-associated waste and its environmental impacts are still unknown. Nevertheless, this will create one of the most problematic environmental pollution ever witnessed on the earth.

4. Ecological health impacts of SARS-CoV-2 in the contaminated environment

Even though the occurrence and transmission of SARS-CoV-2 in the environment, have been extensively studied recently, ecological health impacts of SARS-CoV-2 on their existing environment have not been well explored. It emphasizes the need for more advanced studies to understand the effect of SARS-CoV-2 on different ecosystems, such as aquatic wildlife, soil microorganisms, and plants.

Converging evidence from the pandemic has confirmed the existence of SARS-CoV-2 in water systems for up to several days (Ahmed et al., 2020). Thus, it is doubtful whether the existence of SARS-CoV-2 in aquatic systems could have the possibility to pose threats to aquatic organisms including planktons, nektons, and benthos. A recent study by Malafaia et al. (2020) revealed that aquatic organisms show extreme sensitivity to existing contaminants in their living environments in the early stages of their growth. This was confirmed by Buchwalter et al. (2002) who observed a higher uptake of contaminants by small larvae than its adult due to the higher body surface area to mass ratio of small larvae. A study by Mendonça-Gomes et al. (2021) who investigated behavioral and biochemical effects of two SARS-CoV-2 spike protein peptides on the larval phase of *Culex quinquefasciatus* discovered that short-term exposure (48 h) to a concentration of 40 μg L^{-1} of two peptides have generated behavioral changes in *Culex quinquefasciatus* larvae. An increase in reactive oxygen species production, changes in antioxidant responses, and changes in the olfactory-driven behavior of the *Culex quinquefasciatus* larvae were the changes caused by the existence of SARS-CoV-2 protein peptides in water systems. Induced oxidative stress by SARS-CoV 2 protein-peptide could affect different physiological systems of the animal which then alter the normal functioning of those systems. Further, the presence of SARS-CoV-2 protein peptides in tested samples has altered the acetylcholinesterase activity in larvae which by their silencing could result in a reduction in larval growth, fertility, and malformation. The presence of *Culex quinquefasciatus* in an ecosystem is considered to be very important since their status could indicate the contaminant exposure to ecosystems. A work by Kembro et al. (2009) stated that analysis of behavioral changes of *Culex quinquefasciatus* has been successfully used in toxicological tests. The toxicological effects of SARS-CoV-2 S protein peptides on aquatic animals were evaluated in a further study by Charlie-Silva et al. (2021) using tadpoles from the species *Physalaemus cuvieri*. After an exposure of 24 h to concentrations of 100 and 500 ng mL^{-1}, several toxicological effects were shown by tadpoles including increased acetylcholinesterase activity and oxidative stress. In this study, they were able to observe an occurrence of molecular interactions among peptides and acetylcholinesterase, and antioxidant enzymes. Another study on the impacts of peptide fragments of SARS-CoV-2 on the behavior of fish (*Poecilia reticulata*) has shown effects on the growth and development of these animals by induced redox imbalances (Charlie-Silva and Malafaia, 2022). Similar species in the adult stage were tested to evaluate the possible mutagenic and genotoxic effects caused by exposure to SARS-CoV-2 protein peptides (de Oliveira Gonçalves et al., 2022). Results of the study have proved that SARS-CoV-2 peptide fragments have the potential to pose erythrocyte DNA damage and genomic instability in *Poecilia reticulata*. Fernandes et al. (2021) who assessed the harmful effects of SARS-CoV-2 in aquatic ecosystems, using the species *Danio rerio* (zebrafish) as an animal model demonstrated that species injected with SARS-CoV-2 spike protein fragments were having severe damage to the liver, kidney, ovary, and brain tissues, and mortalities. Further, they have concluded that adverse toxic effects on this species could be due to the genetic homology between zebrafish and human where human shows similar severity in the case of SARS-CoV-2 infection. Therefore, this species could use in future studies to assess the harmful effects of SARS-CoV-2 in the aquatic environment, and at the same time to understand valuable information about vaccine responses and therapeutic approaches in human medicine. Similarly, in another study on the detection of SARS-CoV-2 in marine environments, they have used two bivalve molluscan species of genus *Ruditapes* to determine the presence of SARS-CoV-2 (Polo et al., 2021). SARS-CoV-2 RNA has been detected in studied clam samples confirming the possible contamination of SARS-CoV-2 with marine organisms besides representing their suitability to use as a bio-indicator of coastal water pollution. Not only aquatic invertebrates, but also different mammalian species have been tested for their viral infection and other alterations caused by the persistence of SARS-CoV-2 in their living ecosystems (Audino et al., 2021). The presence of SARS-CoV-2 in the marine environment puts marine animals at high risk for infection. Previous studies have confirmed the occurrence of pathogens inside marine mammals' bodies which are having terrestrial origins suggesting their transmission through sewage to water bodies from land (Grattarola et al. 2016, 2019). The findings of these studies confirm the eco-toxicological effects of SARS-CoV-2 on several aquatic organisms including invertebrates and mammals. Even though these animals do not act as hosts for SARS-CoV-2 their infection and further damages to their health should be thoroughly considered, since it can finally affect the health of natural ecosystems. Up to now, there are a very limited number of studies on these aspects, and a vast 'gray area' is still unrevealed such as mechanisms or pathways for entry of virus to bodies of aquatic organisms. There is an urgent

need for studies on the eco-toxicological effects of SARS-CoV-2 on aquatic organisms by which we could understand the real magnitude of impacts of SARS-CoV-2 on aquatic biodiversity.

These findings prove that the presence of viruses such as SARS-CoV-2 in the different ecosystems could generate an ecological imbalance in the environment.

Apart from aquatic environments soil ecosystems also need to be assessed for the presence of SARS-CoV-2 and its ecological impacts. Soil health is closely linked with soil organic matter which can lead to a reduction in soil productivity (Lal et al., 2020). In soil, virus abundance can reach a number of 10^{10} g^{-1} soil depending on soil properties and virus characteristics (Williamson et al., 2017). The impacts of viruses on soil micro-biome could be either positive or negative. For example, the presence of bacteriophages reduces the abundance of soil bacteria which could be either pathogenic or beneficial for the soil ecosystem (Zhao et al., 2019). In further, the existence of viruses in soil affects the distribution of other soil microorganisms. Viruses can occupy soil pores larger than nano-pores since they are 10–100 times smaller than bacteria (Kuzyakov and Mason-Jones, 2018). Soil microbial communities are important for soil resilience which is the main element of overall soil health and quality of the soil. The loss of soil health will finally affect human health. Therefore, it is urgent to perform further investigations on indirect effects inferred by SARS-CoV-2 on soil eco-systems suggesting measures that can adopt to mitigate the harmful effects.

5. Strategies to reduce the contamination – way forward

5.1. Solutions to reduce the mask waste

Since plastic is a non-biodegradable material, people have considerable controversy regarding different management methodologies to control this waste (Thompson et al., 2009). To explore alternative solutions for mask waste reduction, recovering the energy content of plastics for another useful purpose was identified. Thus, medical waste incineration was recommended (Klemeš et al., 2020). According to the WHO guidelines, 900 °C and 1200 °C temperatures would guarantee safe destruction, but there may be problems with dioxin and furan trace emissions.

However, Liang et al. (2021) stated that reuse and recycling are the best solutions for plastic waste management, but it is essential to follow cleaning or repair steps before determining the plastic conditions. In the conventional process, initially, collected plastics were shredded and sorted using a range of techniques, including spectroscopy, X-ray fluorescence, flotation, magnetic or density separation, and respective color needs to be identified using an optical sorter. Then, separated plastics can be melted and made into pellets to reuse and sold to local plastics manufacturing organizations to produce a range of products such as textiles, footwear, engine oil, and concrete additives. Since this process requires significant capital involvement, it is better to have an automated separation process before shredding (Williams-Wynn and Naidoo, 2020).

Despite their potential threat to ecosystems, removing nano- and microplastics from water has proven to be challenging due to their small sizes and the lack of unified methods. To remove nanoplastics from wastewater and drinking water, both stable methods including filtration, centrifugation, membrane separation, biodegradation, coagulation, and sedimentation, as well as more innovative technologies such as advanced oxidation processes, are used (Devi et al., 2022). The removal of nanoplastics/microplastics is made possible by advanced filtration techniques namely membrane filtration and ultrafiltration (Gupta et al., 2021). Interestingly, the filtration process of drinking water with sand and granular activated carbon with a coagulation process improved the removal of nanoplastics to >99%, where it only removed 88.1% of nanoplastics without coagulation (Arenas et al., 2022). This demonstrates that employing a combination of techniques makes removing nano- and microplastics more effective. The membrane bioreactor has been suggested in bioreactor techniques for the removal of nanoplastics. It uses biological catalysts like enzymes and bacteria, with the coupled separation process being carried out by the membrane system (Ali et al., 2021). Nanoplastics/microplastics can be removed to a limited extent using conventional techniques such as gravity settling, cloud point extraction, field flow fractionation, pressured flow extraction, and thermal hydrolysis (Cerasa et al., 2021). Emerging nanotechnology uses a variety of nanomaterials, including chitosan, metallic, polymer-based, zeolite, magnetic, carbonaceous, ferrite, and metal oxide to remove nanoplastics and microplastics from wastewater and drinking water by their adsorption on surfaces (Tahoon et al., 2020). Additionally, photocatalytic degradation has been utilized to remove plastic materials by breaking them into low molecular weight components (García-Montelongo et al., 2014). Emerging electrochemical techniques are among the technologies that have attracted the most interest because of their simple implementation, high efficiency, eco-compatibility, onsite operation, etc. The removal of microplastics/nanoplatics by electrochemical techniques, such as electrocoagulation, electroadsorption, electrokinetic separation, and electrochemical degradation, have shown tremendous promise in recent years (Chen et al., 2022).

In South Korea, a unique safe waste management plan was developed to manage COVID-19 waste. They recommended that COVID-19 waste cannot be kept for more than one day and must be incinerated within the same day of collection. With that, immediate incineration should proceed above 1100 °C of temperature conditions (Sangkham, 2020). Additionally, microwave and autoclave techniques can often be used for disinfection.

The Philippines has taken a different approach to treat waste during the COVID-19 pandemic. They established special transporters, treatment, storage, and disposal facilities for handling health care waste and its disposal on the island of Luzon. In addition, there is a specific place to collect pathological and infectious waste for smooth handling and avoid any contamination. Each transporter is required to pass through a particular checkpoint and provide all the details and documents (Das et al., 2021).

In addition, research has been accelerated to find opportunities to reuse face masks. With that, a mask rotation strategy was recommended; at first, masks should be dried for more than 72 h. Then decontamination is required to be carried out using different techniques, including UV treatment, hydrogen peroxide (H_2O_2) vaporization, moist heat, and dry heat (Chua et al., 2020; Vanapalli et al., 2021). These recycled masks can be reused in their original structure and others can be re-melted to produce composite products. However, re-processing of waste masks consumes significant capital, and the quality of the mask also reduces; thus, it is essential to consider further precautions to reduce the COVID-19 pressure on the environment.

Using biodegradable masks is another valuable solution to avoid plastic pollution during the pandemic. Hence, polypropylene masks can be replaced with organic materials, including bioplastics and biodegradable polymers which are derived from biological substances that are not harmful to the environment. However, it is essential to consider specific factors such as elasticity, water resistance, and filtering characteristics before using them as an alternative. Hence, scholars confirmed that all these requirements can be met by using biodegradable materials in masks, and they further stated that these materials could reduce 30%–70% of CO_2 emissions compared to other plastic-based masks (Lackner, 2015).

5.2. Environment-friendly disinfection technologies

Waste should be categorized and collected separately into bins or bags at its origin to reduce the spread of infection. Then it should be disinfected and sealed in double-layered plastic bags (generally yellow color) before transporting waste to a treatment facility. The waste can be treated at the facility at using high temperature and the remaining products can be safely disposed of (Fig. 4).

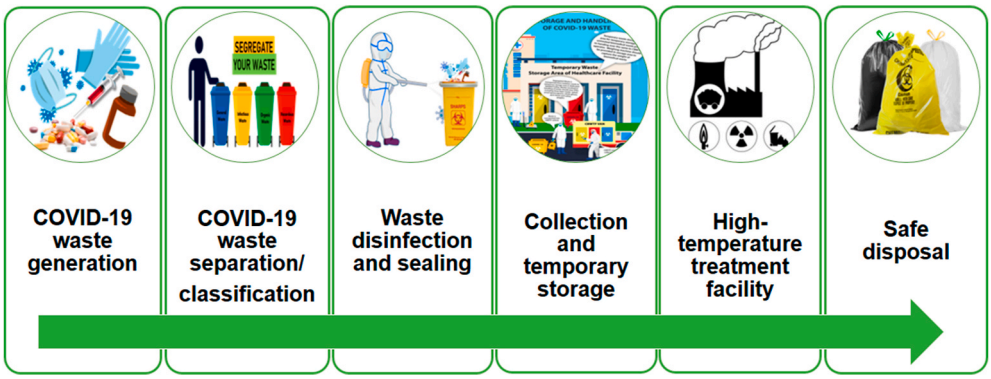

Fig. 4. Schematic diagram of hospital solid waste management.

During the process, it is essential to disinfect storage areas, and transport vehicles to ensure workers' safety. Specific factors must be considered for the disinfection process, including quantity, waste types, costs, maintenance requirements, etc., and suitable technologies should be selected (Ilyas et al., 2020). Fig. 5 represents the process of selecting a disinfection technology based on the influencing factors.

5.3. Novel wastewater treatment technologies

5.3.1. Disinfection using incineration

In this process, waste combustion under high temperatures in the range of 800 °C–1200 °C occurs where 90% of pathogens are removed from organic matter (Datta et al., 2018). Generally, incineration at >1100 °C is the most common condition for managing COVID-19 waste, and sometimes the residuals are again re-incinerated. However, scientists recommend combining an incineration facility with a flue gas treatment facility to gain additional benefits (Ilyas et al., 2020).

5.3.2. Disinfection using thermal techniques

Generally, there are two standard methods: high-temperature pyrolysis and medium-temperature microwave technique. Scholars debate that pyrolysis has more technical benefits than the usual incineration process since it operates under 540–830 °C temperature conditions (Datta et al., 2018). Similarly, other benefits include low emission rates, inert residual, 95% waste volume reduction, and 90% mass reduction, which can be identified as a better technique for COVID-19 waste management.

In addition, the microwave technique can operate under 177 °C–540 °C temperature conditions to break organic matter in wastes while applying high-energy microwaves under an inert atmosphere (Haque et al., 2021; Wang et al., 2020a). The main advantages of this process are low energy requirement, limited heat loss, less environmental impact, and no toxic residuals after the disinfection process. In addition, some researchers suggest that it is beneficial to use the microwave technique by combining the autoclaving process to get effective results (Ilyas et al., 2020).

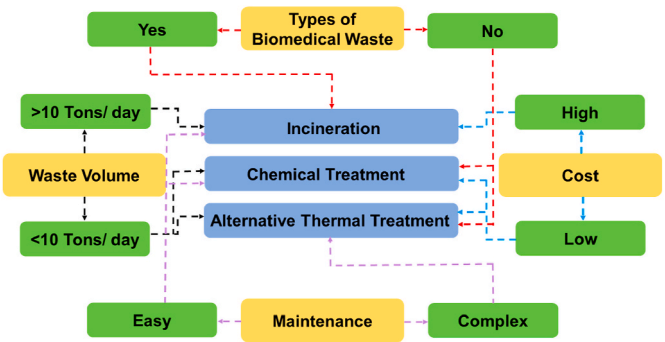

Fig. 5. Selection of disinfection technologies based on the influencing factors.

5.3.3. Chemical disinfection technique

This is a widely applicable technique in many parts of the world where chlorine and non-chlorine chemicals are used to decompose or inactivate the viral or any infectious microorganisms from waste. Chemical disinfection is considered more effective than other techniques due to advantages such as low concentration, stable performance, and rapid actions with no residual hazards (Wang et al., 2020a). NaOCl, ClO_2, and H_2O_2 are commonly used as disinfection media for these processes. In addition, scholars recommend that it is essential to disinfect personal protective to inactivate virus particles. Notably, it is essential to use an appropriate temperature due to heat-sensitive properties that cause harmful results.

Hence, all these facts raise the need for potential solutions to combat the environmental concerns that arise from COVID-19.

6. Conclusions and future research directions

SARS-CoV-2, a novel human coronavirus that emerged in the city of Wuhan, China in later 2019 has now become a global pandemic raising distressing consequences on human health and the economy which will also spill over to environmental issues. Scientists and researchers working in many different disciplines are making effort not only to treat COVID-19 infected patients but also to understand the challenges that occurred with the pandemic on different aspects such as the environment and the influence that the environment generates on the survival and behavior of the SARS-CoV-2 virus to attain sustainable strategy to manage future global crises. The evidence-based knowledge presented here clearly indicates the occurrence of SARS-CoV-2 in different environmental compartments including wastewater and soil signifying the role of the environment in the COVID-19 transmission process. However, the majority of these studies do not identify the infectivity of detected viral genomes, which may be influenced by existing factors in different environmental systems. This raises a serious difficulty with the work done so far, namely that it is not always able to confirm the transmission of infectious SARS-CoV-2 in the environment. This necessitates the need for epidemiological conclusions on the potential transmission of SARS-CoV-2 via environmental routes based on concrete practical applications. The presence of SARS-CoV-2 in the environment not only poses a risk of transmission; it has also been linked to several eco-toxicological effects. Being the most crucial global health calamity of the century, the COVID-19 pandemic has also brought with it a slew of environmental challenges. Excessive use of disinfectants and pharmaceuticals during the past three years has badly affected the quality of water systems in many countries. In addition, researchers found that the COVID-19 epidemic increases 102.2% of waste generation in private and public hospitals, alarming that this will create one of the most

problematic environmental pollution ever witnessed on the earth. In this context, potential strategies should adopt to overcome the existing and future environmental challenges from COVID-19 since human and planetary health are intimately interconnected. This study has highlighted several such measures including the use of environment-friendly disinfection technologies, implementing of novel wastewater treatment technologies including thermal treatment, and employing measures to reduce the production of plastic wastes for example reuse and recycling of plastics. The future scope of work on this aspect should be increased to demonstrate the usefulness of such measures in reducing the harmful effects on the environment. Scientists must devote the majority of their efforts to acting as knowledge brokers, facilitating a common goal-oriented discussion in society to convince people that "our future is determined by what we do now". Thus the world will be able to overcome the worst consequences of the COVID-19 pandemic, assuring a sustainable future.

Author contribution

Anusha Ekanayake: Writing the first draft, writing-reviewing and editing, visualization; Anushka Upamali Rajapaksha: Conceptualization, supervision, writing-reviewing, and editing; Choolaka Hewawasam: Writing the first draft, visualization; Uttpal Anand: Writing the first draft, reviewing and editing, visualization; Elza Bontempi: Writing the first draft, visualization; Sudarshan Kurwadkar: Writing the first draft, visualization; Jayanta Kumar Biswas: Reviewing and editing; Meththika Vithanage: Conceptualization, writing-reviewing and editing, supervision.

Declaration of competing interest

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

Data availability

No data was used for the research described in the article.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.envres.2022.114496.

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