Hygiene and Environmental Health Advances 3 (2022) 100006

Contents lists available at ScienceDirect

Hygiene and Environmental Health Advances

journal homepage: www.elsevier.com/locate/heha

Elucidating the role of environmental management of forests, air quality, solid waste and wastewater on the dissemination of SARS-CoV-2

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A R T I C L E I N F O

Keywords:
COVID-19
Deforestation
Transmission
Air pollution
Medical waste
Wastewater

A B S T R A C T

The increasing frequency of zoonotic diseases is amongst several catastrophic repercussions of inadequate environmental management. Emergence, prevalence, and lethality of zoonotic diseases is intrinsically linked to environmental management which are currently at a destructive level globally. The effects of these links are complicated and interdependent, creating an urgent need of elucidating the role of environmental mismanagement to improve our resilience to future pandemics. This review focused on the pertinent role of forests, outdoor air, indoor air, solid waste and wastewater management in COVID-19 dissemination to analyze the opportunities prevailing to control infectious diseases considering relevant data from previous disease outbreaks. Global forest management is currently detrimental and hotspots of forest fragmentation have demonstrated to result in zoonotic disease emergences. Deforestation is reported to increase susceptibility to COVID-19 due to wildfire induced pollution and loss of forest ecosystem services. Detection of SARS-CoV-2 like viruses in multiple animal species also point to the impacts of biodiversity loss and forest fragmentation in relation to COVID-19. Available literature on air quality and COVID-19 have provided insights into the potential of air pollutants acting as plausible virus carrier and aggravating immune responses and expression of ACE2 receptors. SARS-CoV-2 is detected in outdoor air, indoor air, solid waste, wastewater and shown to prevail on solid surfaces and aerosols for prolonged hours. Furthermore, lack of protection measures and safe disposal options in waste management are evoking concerns especially in underdeveloped countries due to high infectivity of SARS-CoV-2. Inadequate legal framework and non-adherence to environmental regulations were observed to aggravate the postulated risks and vulnerability to future waves of pandemics. Our understanding underlines the urgent need to reinforce the fragile status of global environmental management systems through the development of strict legislative frameworks and enforcement by providing institutional, financial and technical supports.

1. Introduction

The presumptive role of unsustainable environmental management in COVID-19 dissemination and increasingly frequent zoonotic diseases is a withering indication of humanity's destructive relationship with the environment (Ali, 2020; Everard et al., 2020). Environmental management has a significant role in reducing transmission of infectious diseases by acting as critical sanitary barrier and through the reduction of pollution and control of climatic factors (Espejo et al., 2020). The importance of the role of environmental management in disease control was clearly evidenced in previous infectious disease outbreaks especially for vector borne diseases such as malaria and dengue fever (Utzinger et al., 2001; Toledo et al., 2011). The presumed emergence of COVID-19 from zoonotic natural host in conjunction with other increasingly frequent zoonotic diseases point towards the unsustainable management of forests and decline of biodiversity due to human encroachment in pristine natural habitats (Domingo, 2021; Jorwal et al., 2020; World Wildlife Fund (WWF), 2021a, World Wildlife Fund (WWF), 2021b). Since the 1980s, a significant increase in the number and diversity of infectious zoonotic disease outbreaks have been observed and 700,000 viruses were estimated from high-risk viral families which pose zoonotic potential, indicating the possibility of recurrence of similar incidents (Smith et al., 2014; Wigginton and Boehm, 2020). The detection of SARS-CoV-2 RNA in solid waste materials, air samples and wastewater along with the prolonged persistence of SARS-CoV-2 on solid surfaces and bioaerosols under laboratory conditions have raised concerns of COVID-19 transmission through environmental compartments (Di Maria et al., 2021; Setti et al., 2020a; Hu et al., 2020; Van Doremalen et al., 2020; Kasloff et al., 2021). Numerous epidemiological studies have reported correlations between air pollutants and

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https://doi.org/10.1016/j.heha.2022.100006
Received 26 January 2022; Received in revised form 13 April 2022; Accepted 30 April 2022

COVID-19 severity (Perone, 2021; Filippini et al., 2021; Amoroso et al., 2022; Wu et al., 2020; Yao et al., 2021). This indicates that low ambient air quality resulting from deforestation, industries, power generation, transportation, domestic burning and deforestation-induced wildfires can lead to broad negative respiratory impacts which can exacerbate COVID-19 susceptibility by affecting human immune response, lung function and overexpression of angiotensin-converting enzyme 2 (ACE2) receptor (Brancalion et al., 2020; Ellwanger et al., 2020; De Oliveira et al., 2020; Turner et al., 2020; Zoran et al., 2020b; Mataveli et al., 2021). The above concerns are exacerbated by the situational status of the global level of environmental management which is currently at an inadequate level especially in underdeveloped countries. Increasing levels of deforestation are observed globally, for instance, between 2004 and 2017, over 43 million hectares of forest were lost (Pacheco et al., 2021). Similarly, one-third of the world's countries have no legally mandated outdoor air quality standards and institutional responsibility for attaining standards is weak globally (United Nations Environment Programme (UNEP) 2021a). The basic waste management services were available in only 27% of health-care facilities in the least developed countries and 3 billion people lacked controlled waste disposal facilities (Bellizzi et al., 2020; Sharma et al., 2020; Almulhim et al., 2021). These problems could be further aggravated as previous sustainability agreements are anticipated to be relaxed during the COVID-19 pandemic to safeguard agricultural production and economic recovery efforts (Brancalion et al., 2020). Preventive measures targeted at COVID-19 control have mainly prioritized public health safety measures and the overarching environmental implication of the pandemic is largely understated (Kareem et al., 2021). Efforts for environmental management during COVID-19 mainly focuses to prevent disease transmission through environmental compartments (Kang et al., 2021). This calls for the imperative need to focus the problem of increasingly frequent infectious diseases from a wider perspective for incorporating appropriate strategies in disease management. Even though the causative factors have deep rooted interlinks with different aspects of environmental management at various levels, only very few studies have covered these relationships comprehensively. Notably, Al Huraimel et al. (2020) explored the plausible transmission mechanisms through environmental management along with the potential of environmental management aspects for predicting pandemic severity through wastewater surveillance and atmospheric pollution. The facets of forest management particularly for COVID-19 are scantily explored in literature integrally with other environmental management aspects despite the impacts of biodiversity loss on zoonotic diseases being covered abundantly. The aim of this review is to analyze the latest evidence on occurrence, survival, and behavior of SARS-CoV-2 virus in various environmental compartments such as forests, outdoor air, indoor air, solid waste, and wastewater along with relevant data from past disease outbreaks to frame effective environmental managements strategies for combating future pandemics.

2. Impact of ambient environments on SARS-CoV-2

A preprint by Wang et al. (2020b) reported that increase in minimum ambient air temperature by 1 °C, lead to decreasing number of COVID-19 cases by 0.86% in Chinese cities. It must be noted that higher temperatures alone do not imply decreased transmission of transmission of SARS-CoV-2 (To et al., 2021). Air pollution, along with low wind speeds and temperatures, have shown to lead to higher transmission of SARS-CoV-2, more in industrial regions than coastal regions (Bolaño-Ortiz et al., 2020). Even though SARS-CoV-2 has been stated to survive in lower temperatures than higher temperatures, humidity has been shown to have a higher impact on its transmission (Aboubakri et al., 2022; Crema, 2021). Out of climatic factors and population density, it has been found that climatic factors have a bigger contribution within the transmission of SARS-CoV-2 in the following order: humidity; precipitation; pressure; wind; temperature; solar irradiation (Spada et al., 2021). On the other hand, higher humidity paired with higher temperatures in indoor spaces have shown to reduce the lifetime of respiratory droplets carrying SARS-CoV-2 virus (Shadloo-Jahromi et al., 2020).

It must also be noted that reported that factors of climate change such as increasing atmospheric CO_2 levels and temperatures, notable differences in precipitation patterns and lower cloud covers in regions creates optimal environments for bats within regions with forest-like habitats such as Central Africa, Central and South America, Southern China and Southeast Asia, potentially leading to higher transmission of SARS-CoV-2 (Beyer et al., 2021). Additionally, lack of management of air quality, wastewater and solid waste may potentially contribute to SARS-CoV-2 transmission and impacts (Anand et al., 2021b; Mathavarajah et al. 2021; Pegoraro et al., 2021; Travaglio et al., 2021, United Nations Environment Programme (UNEP) 2021a; World Health Organization (WHO) 2021b). Secondary transmission routes are also plausible. For example, air quality can be reduced due to higher levels of pollutants from wildfires and other activities, which have shown to lead to strong impacts upon contracting COVID-19 (Liu et al., 2020a; Meo et al., 2020; Middleton, 2020; Curtis, 2021; Dragone et al., 2021; Kiser et al., 2021; Leifer et al., 2021; Setti et al., 2020b; Zhou et al., 2021a). Furthermore, natural ventilation for optimal indoor air quality is not sufficient to control the potential spread of SARS-CoV-2 (Li et al., 2004; Meiss et al., 2021a; World Health Organization (WHO) 2021a). The host of SARS-CoV-2 may contribute to its spread (De Wit and Ricketts, 2021) through means of water from agriculture (Coronado et al., 2021) or organic human waste (De Wit and Ricketts, 2021), which may affect marine ecosystems (Guo et al., 2021; Mathavarajah et al. 2021) and individuals through buildings (Wang et al., 2021).

Differences in SARS-CoV-2 testing accessibility due to lower income levels, minority groups, distance of residential areas to testing sites and accessibility to healthcare may lead to inaccurate or ill-timed data of SARS-CoV-2 transmission (Rader et al., 2020). Hence, national public health testing requirements must consider disadvantaged sociodemographic factors for higher accuracy and timely data for SARS-CoV-2 transmission (Rader et al., 2020). Additionally, safety within laboratories that engage in SARS-CoV-2 diagnosis is essential to reduce SARS-CoV-2 transmission (Mourya et al., 2020). Requirements should include permitting trained staff for the handling of SARS-CoV-2 specimen according to national and WHO guidelines, within laboratories of BSL-2 (Biosafety Level 2) standards (Mourya et al., 2020).

Despite climatic and population factors majorly contributing to the spread of SARS-CoV-2, governments must frame public policies to protect health of citizens, rather than the sole reliance on environmental and population conditions for the control of the spread of SARS-CoV-2 (Smith et al., 2021). Additionally, research and strategies for environmental SARS-CoV-2 transmission, along with the need of inclusive policies for waste management, wastewater management, indoor and outdoor air quality, land management and forest conservation are essential and must be highly considered for implementation.

3. Deforestation

3.1. Linkages between infectious disease dissemination and deforestation

Even though the exact source of SARS-CoV-2 is unclear, COVID- 19 is considered to emerge from an original wildlife host (Petrovan et al., 2021). This plausible wildlife origin is a major concern from a management perspective as infectious diseases are increasingly reported to be associated with wildlife hosts. Global analysis of emerging infectious diseases (EIDs) conducted by Jones et al. (2008) from 1940 to 2004 found that the majority (60.3%) of EID events were caused by zoonotic pathogens, of which 71.8% were from pathogens with a wildlife origin. Studies that clearly demonstrate the effects of deforestation and COVID-19 at the origin are currently not available in literature as observed with certain other zoonotic diseases. For instance, slash-and-burn deforestation preceding Nipah virus outbreak in Southeast Asia drove fruit bats from their forest homes into nearby cultivated fruit orchards (Chua et al., 2002). This resulted in Nipah infection in pigs through consumption of fruits partially eaten by bats which in turn led to human infection (Chua et al., 2002). Olivero et al. (2017) employed remote sensing techniques to find the effects of deforestation with 27 Ebola virus disease (EVD) outbreaks (27 out of 40, where index cases were identified) and found that outbreaks located along the limits of the rainforest biome were significantly associated with forest losses within the previous 2 years. Similarly, Rulli et al. (2017) showed that in EVD outbreaks, the index cases in humans occurred mostly in hotspots of forest fragmentation. However, the effect of deforestation on zoonotic disease emergence must be viewed in a broader scale as it could cause biodiversity loss, zoonotic reservoir's habitat modification, increased frequency of human and domestic animal contact with wildlife reservoirs of potential zoonoses and environmental damage (Wolfe et al., 2005; Platto et al., 2021a; De Wit and Ricketts, 2021). These conditions for zoonotic disease emergence are of general nature and can be applied to COVID-19, also due to involvement of plausible mediators such as bats (Platto et al., 2021a). Current literature that directly associates COVID-19 and deforestation is the evidence for SARS-CoV-2 like viruses in zoonotic wild hosts, along with few studies analyzing loss of ecosystem services from deforestation and COVID-19 severity (Meo et al., 2020; Murakami et al., 2020; Roviello and Roviello, 2020; Zhou et al., 2020; Firebaugh et al., 2021; Kiser et al., 2021; Leifer et al., 2021; Roviello and Roviello, 2021; Wacharapluesadee et al., 2021; X. Zhou et al., 2021a; H. Zhou et al., 2021b).

3.2. Zoonotic evidence of SARS-CoV-2

Even though research about animal reservoir of SARS-CoV-2 is evolving and has not been validated, available studies are pointing towards zoonotic natural origins of SARS-CoV-2 with horseshoe bats (Rhinolophus*)* as plausible natural reservoir and pangolins as an intermediate host of the coronavirus (Domingo, 2021; Jorwal et al., 2020; Zhang and Holmes, 2020). Different bats of the genus Rhinolophus were reported to host viruses phylogenetically similar to SARS-CoV-2 in China (*Rhinolophus affinis, Rhinolophus pusillus* and *Rhinolophus malayanus*), Cambodia (*Rhinolophus shameli*), Japan (*Rhinolophus cornutus*) and Thailand (*Rhinolophus acuminatus*) (Murakami et al., 2020; Zhou et al., 2020; H. Zhou et al., 2021b; Wacharapluesadee et al., 2021). A preprint by Temmam et al. (2021) reported three viruses (BANAL-52, BANAL-103 and BANAL-236) from Rhinolophus bats in North Laos which are more than 95% identical to early strains of SARS-CoV-2, and BANAL-52 is 96.8% identical to SARS-CoV-2. Particularly, the receptor binding domains of these viruses are almost identical to that of SARS-CoV-2, that may lead to direct transmission to humans despite the absence of the furin cleavage site in SARS-CoV-2 spike protein that further aids viral entry to human cells (Temmam et al., 2021). These results bolster the postulations of natural origin of SARS-CoV-2, whilst exacerbating the concerns over the potentially circulating human infective coronaviruses (Mallapaty et al., 2021). In addition, two sub lineages of SARS-CoV-2 were hosted by Malayan pangolins (*Manis javanica*), pangolin-CoV-GDC with genomic similarity of 90.1% and pangolin-CoV-GXC with genomic similarity of 85% to SARS-CoV-2 (Xiao et al., 2020a; Lam et al. 2020). In Thailand, SARS-CoV-2 neutralizing antibodies were detected in a pangolin (Wacharapluesadee et al., 2021). SARS-CoV-2 was also detected in other animals including *Panthera tigris, Panthera leo, Neovison vison, Macaca mulatta* and *Phodopus sungorus* (Enserink, 2020; Keesing and Ostfeld, 2021). These animals are believed to have transmitted SARS-CoV-2 from humans, and of this, minks appeared to be able to transfer SARS-CoV-2 back to humans (Enserink, 2020; Keesing and Ostfeld, 2021). Presence of SARS-CoV-2 like viruses in multiple animal species indicate that wider dissemination and future involvement of multiple animal species in SARS-CoV-2 circulation and persistence are plausible (Haider et al., 2020; Poudel, 2020).

3.3. Loss of forest ecosystem services and COVID-19

Roviello and Roviello (2020) evaluated Italian regions with different forest coverage per capita and found lowest mortality rates of COVID-19 in areas with forest per capita ratio higher than 0.5 ha/person, suggesting that evergreen Mediterranean forests and shrubland plants provided protective effect by the emission of immunomodulating volatile organic compounds (VOCs) and provision of dietary sources of bioactive compounds. Roviello and Roviello (2021) supports the findings of Roviello and Roviello (2020) as they analyzed the affinity of Mediterranean plant-emitted VOCs such as isoprene, α-pinene, linalool and limonene for COVID-19 protein targets by molecular docking modeling, suggesting that plant organic compounds were able to bind and interfere with the complex formed by the receptor binding domain of the coronavirus spike protein with the human cell receptor. Roviello et al. (2021) suggested that the double protective role of trees through emission of biogenic volatile organic compounds (BVOCs), interception of particulate matter on leaves and surfaces may enable reduction of COVID-19 induced mortality. In another study, Laudares and Gagliardi (2020) analyzed the potential of deforestation and spread of COVID-19 affecting indigenous people and found that deforestation of 1 km^2 area resulted in 9.5% new COVID-19 cases. Association between wildfire incidences with COVID-19 cases and severity has been reported even though the number of these correlation studies were observed to be less compared to wider literature on ambient air pollution and COVID-19 (Meo et al., 2020; Firebaugh et al., 2021; Kiser et al., 2021; Leifer et al., 2021; X. Zhou et al., 2021a). Of this, Meo et al. (2020) found that wildfire allied pollutants, particulate matter $PM_{2.5}$ and CO is associated positively with COVID-19 daily cases and cumulative deaths. Amplification effect of COVID-19 cases (Kiser et al., 2021; Leifer et al., 2021; Zhou et al., 2021a) and deaths (Zhou et al., 2021a) were observed to be associated with elevated $PM_{2.5}$ from wildfires. However, the variations of individual exposures to wildfires due to factors such as occupation or income were not accounted in these studies.

Deforestation could result in forest fragmentation and biodiversity loss which can proliferate viral transmission. For instance, it was found that infection prevalence of hantaviruses in wild reservoir (rodent) populations and reservoir population density increased when small-mammal species diversity was reduced (Suzán et al., 2009). Johnson et al. (2009) showed that heterospecific communities cause a 25% – 50% reduction in the Schistosoma mansoni infection among snail hosts under constant host density. This could be due to “dilution effect” that occurs when high host diversity exists and negatively affect pathogen persistence as high host abundance act as buffering species under specific conditions and context (Platto et al., 2021b; Petrovan et al., 2021). Haddad et al., 2015 demonstrated that habitat fragmentation reduces species richness by 13% to 75% through fragmentation experiments covering five continents, multiple biomes and scales over 35 years. In addition, certain taxa are more likely to be zoonotic hosts than others and evidence suggests that human-modified landscapes tend to favor their prevalence (De Wit and Ricketts, 2021). For instance, bats are much adapted to anthropized environments such as houses, barns, cultivated fields and orchards, therefore spillover from disturbed forest habitats is very likely (Platto et al., 2021a, 2021b). Agricultural and urban land-use types support these zoonotic reservoirs by providing nutrient subsidies in the form of mineral agricultural runoff or human organic waste (De Wit and Ricketts, 2021). Wide distribution of SARS-like-CoV carriers in horseshoe bat species, prevalent bat hunting practice and wildlife trade in South China, Southeast Asia, Africa and some Pacific Islands create immense opportunities of viral transmission between bats and other animals (Hassanin et al., 2020; Platto et al., 2021b).

3.4. Strategies to combat deforestation to prevent future pandemics

Complex links and trade-offs among global forest, biodiversity and public health goals calls for a holistic approach for restoring the synergy in ecosystems as an important frontier in the management of zoonotic disease risk (Keesing and Ostfeld, 2021). The One Health Approach advocates the necessity of incorporating interlinks between human health, animal health and environmental factors into actions, policies, legislation, and research to combat pandemics (Jorwal et al., 2020). However, the institutional support for the One Health Approach is uneven. For instance, the initiatives to develop capacities in disease management in Africa lags behind Asia (United Nations Environment Programme (UNEP) 2020b). Therefore, prioritizing this approach in post COVID-19 recovery programs by close cooperation and interaction between all the stakeholders including veterinarians, occupational health physicians and public health operators such as policy makers, scientists, communicators, health financiers and geographers is necessary (Rabozzi et al., 2012; Kahn, 2020; Muraina, 2020; Pacheco et al., 2021). Data sharing and communication among relevant sectors must be ensured for collaboration towards integrated forest management policies to reduce risks of infectious disease (Cardil et al., 2020; Otu et al., 2021). To bring transformative changes, countries must identify the gaps in financial, human and material resources towards One Health Approach policies, guidelines and strategic plans. Rigorous assessments of emerging viruses, ecological health, disease ecology, eco-evolutionary dynamics, wildlife population dynamics, synergies between human behavior and ecological communities, outbreak investigation and preparedness strategy knowledge must be conducted through accelerated research and development (Nabi et al., 2020; Keesing and Ostfeld, 2021; De Wit and Ricketts, 2021). Serious financial limitations from COVID-19 economic turndown could be experienced by regions that rely on funding from a single sector such as international tourism to sustain biodiversity conservation activities (Bates et al., 2021). The economic case by Dobson et al. (2020) for lowering deforestation and the wildlife trade estimated that the annual costs of programmes to reduce deforestation and the wildlife trade and build pandemic surveillance in disease hotspots would be \$17.7bn – \$26.9bn, which is more than three orders of magnitude smaller than the current estimate cost of COVID-19 economic damages which is \$8.18tn - \$15.8tn. Therefore, a shift to a more preventative rather than reactive approach is of paramount importance for long-term risk management to combat future disturbances and substantial economic and long-term environmental benefits (Nabi et al., 2020; Bates et al., 2021). Financial burden on governments to scale up One Health Approach programs could be reduced by public private partnerships by promoting resource sharing and collaboration. Investments to include local community experts and stewardship including indigenous management must also be considered to create long-term capacity building in forest management (Bates et al., 2021). National forest authorities should be strengthened to combat illegal logging and wildlife hunting by strictly enforcing forest laws and governance systems (United Nations (UN) 2020). The forest management sector must prioritize national targets and undertake enabled policies in liaison with the international initiatives such as the UN Strategic Plan for Forests 2030 and the UN Sustainable Development Goals (SDGs) (Rahman et al., 2021). Together with this, integration of education and mass awareness at all levels of society would regain a positive outlook for sustainable land management and forest conservation and reinforce public health structures (Cardil et al., 2020; Food and Agriculture Organization (FAO) 2020; Otu et al., 2021).

4. Outdoor air

4.1. Plausible mechanisms of COVID-19 transmission and severity via outdoor air

Transmission of SARS-CoV-2 virus through airborne droplet nuclei, small virus-laden aerosols less than 5 μm released during respiration, vocalism or evaporation of droplets, to distances > 1 m especially in outdoor settings is a matter of debate (Contini and Costabile, 2020; Anand et al., 2021a). Even though, SARS-CoV-2 viral particles may be found viable up to 3 h after aerosolization in laboratory-controlled environment, the half-life could be different in natural outdoor (non-laboratory) conditions (Contini and Costabile, 2020; Senatore et al., 2021; Wiktorczyk-Kapischke et al., 2021). Variables such as aerosol size, composition of the suspending medium, the lifetime of the virus in the aerosol, minimum amount of viable virus needed to be inhaled to produce infection, sunlight exposure, temperature, humidity, air quality, air velocity and flow rate could significantly influence the dispersion of airborne pathogens (Contini and Costabile, 2020; Dragone et al., 2021; Senatore et al., 2021). One possible mode of effect from outdoor air could be the transmission of COVID-19 in highly polluted areas mediated by outdoor air pollutant particulate matter (PM), which may act as a potential ‘carrier’ for droplet nuclei, triggering a boost effect on the spread of the virus (Setti et al., 2020b; Curtis, 2021; Dragone et al., 2021). Zoran et al. (2021) suggested that the chemodynamics of SARS-CoV-2 virions and PM interactions may be responsible for the COVID-19 pandemic spreading during several seasons, which provides basis for explaining reported correlations between air pollution and COVID-19. Bioaerosol is also a factor for airborne transmission of virus, however, the highly diluted nature of viral bioaerosol in ambient air has been considered a major impediment to COVID-19 transmission through this route (Setti et al., 2020b). Current knowledge about COVID-19 indicates an unlikely probability of transmission through particulates/aerosols in outdoor air which could be due to low respiratory aerosols in outdoor environments (Sunyer et al. (2021). Furthermore, there is no validated evidence on real stability and virulence of SARS-CoV-2 viral particles associated with outdoor air PM or aerosols (Anand et al., 2021a; Dragone et al., 2021). Pertaining to other virus transmission through outdoor air, Zhao et al. (2019) investigated airborne transmission of highly pathogenic avian influenza (HPAI) H5N2 cases of the 2015 outbreak in Iowa (USA). Even though the Iowa recipient sites never exceeded the minimal infective doses for poultry, this study found that majority of the positive cases in Iowa were due to continuous exposure from airborne virus carried by fine particulate matter from infected farms within the state (i.e., intrastate) and infected farms from the neighboring states (Zhao et al., 2019). In another study, Corzo et al. (2013) detected influenza A virus RNA in air samples originated from pig farms collected between 1.5 km and 2.1 km away from the farms with viral levels significantly lower at 4.65E+03 RNA copies/m^3, showing that aerosols released from pig barns can be transported downwind.

Another plausible effect from exposure to outdoor air pollutants could be increased spread of COVID-19 by decreased immune response, lung damage and overexpression of angiotensin-converting enzyme 2 (ACE2), leading to more severe and lethal forms of COVID-19, as well as delays/complications in the recovery of the patients (Alifano et al., 2020; Bourdrel et al., 2021; Comunian et al., 2020; Paital and Agrawal, 2020; Marquès and Domingo, 2021). Upregulation of ACE2 by PM$_{10}$ was found in human alveolar A549 and human respiratory epithelial cells in a non- peer reviewed study (Miyashita et al., 2020). Similarly, Chuang et al. (2020) found that 3 months of exposure to PM$_1$ increased ACE2 expression in rat lungs. In another study, mice treated with PM$_{2.5}$ showed a significant increase in ACE2 expression in the lung 2 and 5 days after instillation (Lin et al., 2018). A “double-hit” hypothesis was proposed by Frontera et al. (2020) which explained effects of combined exposure to elevated outdoor PM$_{2.5}$ and NO$_2$. PM$_{2.5}$ exposure could lead to lung damage, inflammation, increased susceptibility to viral infection and alveolar ACE2 overexpression. Exposure to NO$_2$ can then cause additional lung damage including inflammation and edema, thereby increasing the susceptibility to serious COVID-19 infection (Frontera et al., 2020). It is unclear whether this mechanism requires long- or short-term exposure to air pollution (Kiser et al., 2021). In vitro studies suggest that relatively short exposure to PM$_{2.5}$ may induce cellular changes and inflammation (Kiser et al., 2021). The consequences of exposure to air pollution can thus possibly weaken respiratory system thereby increasing susceptibility to COVID-19 infection (Marquès and Domingo, 2021). Specific linkages between outdoor air and SARS-CoV-2 are complicated and still uncertain, available research in literature is mainly observed as i) laboratory testing of the presence of SARS-CoV-2 in the outdoor particulate matter (PM) and aerosols ii) statistical inference between the air pollutants and COVID-19 severity.

4.2. Presence of SARS- CoV-2 in outdoor air

Presence of SARS-CoV-2 virus RNA in outdoor air is still poorly known and contrasting results are reported. Setti et al. (2020a) detected SARS-CoV-2 RNA in outdoor/ airborne PM_{10} from an industrial site in Italy. This study, however, did not quantify the virus concentrations (Chirizzi et al., 2021). Ambient $PM_{2.5}$ bound SARS-CoV-2 RNA was found in Turkey with concentrations that ranged from 0.1 copies/m^3 to 23 copies/m^3 with highest percentages from hospital garden and from two urban sites by Kayalar et al. (2021). Hu et al. (2020) found positive viral RNA in air samples (China) collected 10 m away from an inpatient and outpatient building, with a concentration range of 0.89 –1.65 $\times$ 10^3 RNA copies/m^3, however, no viable virus was isolated from viral RNA positive aerosol samples. In another study, Zhang et al., 2021a, detected SARS-CoV-2 RNA in aerosols (285 - 1130 copies/m^3) in hospital outdoor environments at departments receiving confirmed or suspected COVID-19 patients and wastewater treatment sector. Differently, Liu et al. (2020b) detected SARS-CoV-2 viral RNA negative in aerosols in outdoor areas of hospitals in Wuhan (<3 copies/m^3) with the exclusion in proximity of a crowded zones hospitals where concentrations up to 11 copies/m^3 were detected. No presence of SARS- COV-2 RNA was detected in outdoor air including residential and urban areas in Italy (Chirizzi et al., 2021; Pivato et al., 2021; Belosi et al., 2021), air samples near medical center in Germany (Dunker et al., 2021), air samples on PM_{10}, $PM_{2.5}$ and PM_1 in Spain (Linillos-Pradillo et al., 2021), air sample in car parking lot near the hospital and sidewalks near the hospitals (Passos et al., 2021) and air samples collected beyond infected mink farms in the Netherlands (De Rooij et al., 2021). The evidence of viral RNA alone is not indicative of the presence of active viruses that could be effectively transmitted. Currently no information is available about real stability and virulence of SARS-CoV-2 viral particles associated with outdoor air PM or aerosols which necessitates further scientific exploration in this direction (Anand et al., 2021a; Dragone et al., 2021).

4.3. Epidemiological studies on outdoor air pollution exposure and COVID-19 severity

Numerous epidemiological studies on outdoor air pollution exposure continue to report significant correlations between urban air pollution due to combustion traffic related products, wildfires or other anthropogenic sources pollutants and natural sources such as desert storms with the increased incidence and/or severity of COVID-19 and/or mortality (Liu et al., 2020a; Meo et al., 2020; Middleton, 2020; Kiser et al., 2021; Leifer et al., 2021). An association of elevated levels of air pollutants such as PM_{10}, $PM_{2.5}$, NO_2, CO, SO_2 and O_3 with increased infectivity and severity of COVID-19 cases was found in various parts of the world including Italy, China, the United States, India, Spain, the United Kingdom, Mexico, India, Malaysia and Singapore (Table 1). These investigations adopted different methodologies for associating COVID-19 with outdoor air pollution, therefore it is not possible to derive definitive conclusions from these studies (Anand et al., 2021a). Most of the available epidemiological studies are aggregated assessments at population levels using air quality data from either satellites or local monitoring stations without any details on individual exposures (Bourdrel et al., 2020). Only few studies analyzed individual level data for evaluating association of air pollutants with COVID-19 (Travaglio et al., 2021; Pegoraro et al., 2021). For instance, Pegoraro et al. (2021) found positive association between PM_{10} levels and the likelihood of experiencing pneumonia by calculating PM_{10} exposure of each patient considering

Table 1
Epidemiological evidence on air pollutants and their associations with Covid 19.

Location	Main results and conclusions	Reference
Italy	NO_2, O_3, PM_{10}, and $PM_{2.5}$ and COVID-19 prevalence positively associated with case fatality rate.	Perone (2021)
	Exceedance of the daily limit value of PM_{10} is a significant predictor of infection.	Setti et al. (2020b)
	Positive non-linear association between NO_2 levels and mortality rates at different time periods.	Filippini et al. (2021)
	Positive non- linear association between NO_2 levels and SARS-CoV-2 incidence.	Filippini et al. (2020)
	• An increase of mean annual concentrations of $PM_{2.5}$ and PM_{10} over the previous years associated with incidence. • Annual mean $PM_{2.5}$ concentration was positively associated with all-cause mortality. • NO_2 levels inversely associated with incidence and all-cause mortality.	De Angelis et al. (2021)
	PM_{10} independently associated with the cases.	Dettori et al. (2021)
	Positive correlations between ozone levels and negatively correlations of NO_2 with total COVID-19 infections, daily new positive and total deaths cases.	Zoran et al. (2020a)
	Results exclude that PM alone was the primary cause of the high CoVid-19 spread rapidity.	Collivignarelli et al. (2021)
	Daily averaged PM positively associated with average surface air temperature and inversely related to air relative humidity on cases.	Zoran et al. (2020b)
	Positive correlation between cases with high concentrations of suspended PM and a negative relationship with ozone.	Dragone et al. (2021)
Europe	A significant statistical association between NO_2 and COVID-19 mortality.	Amoroso et al. (2022)
Spain	A threshold of PM (50 $\mu g/m^3$) determined correlation with COVID-19.	Marquès et al. (2021)
	PM_{10} and NO_2 showed positive association but ozone levels showed negative relationship with daily new COVID-19 cases and deaths.	Zoran et al. (2021)
England	An increase in long-term average of $PM_{2.5}$ associated increase in COVID-19 cases.	Travaglio et al. (2021)
US	AQI-NO_2 were significantly associated with the COVID-19 variables.	Sarmadi et al. (2021)
	Daily maximum eight-hour ozone concentration positively associated with new COVID-19 cases but not with new deaths.	Adhikari and Yin (2020)
	COVID-19 cases and deaths increased with increasing levels of $PM_{2.5}$, CO, NO_2 and O_3.	Meo et al. (2021)
	$PM_{2.5}$ positively associated with COVID-19 death rate.	Wu et al. (2020)
	$PM_{2.5}$ and PM_{10} negatively linked with COVID-19 cases, positively with short-term exposure to O_3 with a lag of 7 days.	Gujral and Sinha (2021)
China	Daily COVID-19 incidence positively associated with $PM_{2.5}$, negatively with PM_{10}.	Jiang et al. (2020)
	Positive correlations between NO_2 concentration and basic reproductive number of COVID-19.	Yao et al. (2021)
Mexico	$PM_{2.5}$ increases the probability of death due to COVID-19.	López-Feldman et al. (2021)
India	Increase in $PM_{2.5}$ exposure associated with increased COVID-19 incidence.	Singh et al. (2020)
Malaysia	COVID-19 cases were positively correlated with PM_{10}, $PM_{2.5}$, SO_2, NO2, CO.	Suhaimi et al. (2020)
Singapore	• $PM_{2.5}$, NO2 and pollutant standards index levels were positively associated with daily COVID-19 cases • PM_{10}, O_3, SO_2, CO levels, rainfall and humidity were negatively associated with daily COVID-19 cases.	Lorenzo et al. (2021)

a specific time-window defined based on COVID-19 registration date. Studies on the potential influence of air pollutants such as VOCs, dioxins and furans, ammonia (NH_3) or metals are not available in the scientific literature (Dragone et al., 2021; Marques and Domingo, 2021). Also, most of these statistical studies have not accounted confounders such as population density, the time of the virus introduction, the time of introduction of infection control measures, spatial and temporal autocorrelation of air pollution and infections (Bourdrel et al., 2021; Anand et al., 2021a). Therefore, further epidemiological studies are needed to better estimate the impact of outdoor air pollution on COVID-19.

4.4. Strategies for outdoor air quality management for combating future pandemics

It is uncertain what fraction of COVID-19 deaths could have been avoided in the absence of air pollution due to presence of other confounding factors, however, plausible association of COVID-19 and other viral infections with air quality deterioration indicate that it is imperative to include air pollution management in long-term follow-up studies for pandemics (Magazzino et al., 2020; Brunekreef et al., 2021). In 2019, more than 90% of the global population lived in areas where concentrations exceeded the 2005 WHO air quality guideline for long term exposure to $PM_{2.5}$ (World Health Organization (WHO) 2021b). Even then, only 33% of the countries impose obligations to meet legally mandated standards (United Nations Environment Programme (UNEP) 2021a). In addition, only 31% of countries have legal mechanisms to address cross border air pollution . Therefore, it is necessary to reiterate the need of accelerating the existing plans and policies, targeting all sources of atmospheric pollution such as industries, home heating and traffic. More governments should frame policies focusing on prominent sources of air pollution and means of controlling air emissions in managing air quality. The specific solutions may vary with countries. For instance, India's ambient air quality standard could be achievable by mitigating household emission sources and rural electrification, whereas China could obtain substantial air quality health benefits from large-scale fleet electrification especially in populous megacities (Ou et al., 2020). Countries with strong policy driven improvements in air quality have often seen marked reduction in air pollution (World Health Organization (WHO) 2021b). For instance, as a result of the implementation of China's clean air policies, the air quality has substantially improved from 2010 to 2017, in which controls on power plants and industries emissions were identified to be the most effective mitigation measures (Zheng et al., 2018). Similarly, it has been shown that periodical revisiting of the Clean Air Act in the US has enabled improvement of the air quality after five decades of its implementation (Greenbaum, 2018). Compared to the US EPA National Ambient Air Quality Standard and the EU Limit Value for $PM_{2.5}$, WHO Global Air Quality Guidelines (AQGs), are more stringent, however, WHO AQGs does not offer complete protection from air pollution risks (Burnett et al., 2018). Considering accumulated evidence on the air pollution effects on different aspects of health, WHO ADGs has been revised from 2005 global update. It is estimated by a rapid scenario analysis performed by WHO that almost 80% of deaths related to $PM_{2.5}$ could be avoided in the world if the current air pollution levels were reduced to those proposed in the updated 2021 guideline (World Health Organization (WHO) 2021b). Recent fitness check assessed that clean air policies in the EU are achieving positive outcomes, however, was recommended to closely align with WHO AQGs (European Union (EU) 2020). Even though air pollution is a threat to health in all countries, nearly 90% of air pollution related deaths occur in low and middle-income countries, with nearly 2 out of 3 occurring in South-East Asia and Western Pacific regions (World Health Organization (WHO) 2016). Direct technical support can be attained from international bodies such as united nations environment program (UNEP) for development and implementation of legal frameworks (United Nations Environment Programme (UNEP) 2021b). Additionally, countries struggling with high air pollution levels may also consider interim targets to facilitate stepwise improvement in air quality and thus gradual, but meaningful, health benefits for the population (World Health Organization (WHO) 2021b). More countries must adopt robust air quality laws, that must include setting ambitious standards in law for both indoor and ambient air pollution, improving legal mechanisms for monitoring air quality, increasing transparency, significantly enhancing enforcement systems and improving policy and regulatory coordination for national and transboundary air pollution (United Nations Environment Programme (UNEP) 2021b). In addition, countries must strengthen international commitments such as the right to a healthy environment including clean air, which is a precursor to achieving Agenda 2030 and Sustainable Development Goals on good health, affordable and clean energy, sustainable cities, responsible production, and life on earth (SDGs 3, 7, 11, 12 and 15) (United Nations Environment Programme (UNEP) 2021b).

5. Indoor air

5.1. Presence of SARS-CoV-2 in indoor air

It is important to consider the researched relationship between SARS-CoV-2 transmission and indoor air as many individuals have been spending more time indoors during the COVID-19 pandemic (Hwang et al., 2021; Qian et al., 2020). SARS-CoV-2 has been reported to travel beyond 2 metres via indoor aerosols by acts such as sneezing, coughing and speaking, and has a half-life for up to 1.2 h, similarly to SARS-CoV (Booth et al., 2005; van Doremalen et al., 2020; Adeniran et al., 2021; Allen and Ibrahim, 2021; Curtius et al., 2021; Grinshpun and Yermakov, 2021). Live SARS-CoV-2 was detected in indoor air of a USA hospital, at a 2 m – 4.8 m distance from patients with at least one positive COVID-19 rRT-PCR test (Lednicky et al., 2021). SARS-CoV-2 RNA has been detected in an exhaust duct surface of a ferry, vehicle air conditioner (AC) and HVAC (Heating, Ventilation and Air Conditioning) filters of dorm and households, and in air samples from health care facilities and patient van, bank, shopping center, government office, airport, subway station, trains and buses in North and South America, Asia and Europe, due to plausible pollution and lack of air disinfection systems, safe distancing and mask use (Mouchtouri et al., 2020; Lednicky et al., 2020; Bazzazpour et al. 2021; Hadei et al. 2021; Jin et al., 2021; Lednicky et al., 2021; Maestre et al., 2021; Passos et al. 2021; Razzini et al., 2020; Sousan et al., 2021). Similarly, SARS-CoV RNA was detected within indoor air and AC (Du et al., 2005).

In addition to testing indoor air for the presence of SARS-CoV-2, its plausible indoor presence has been inferred through testing of individuals attending areas such as a church, building, bar, ferry, concert venue, restaurant, health care facility, fitness centres and buses in Asia, Australia, Europe, South America and Africa, due to plausible reasons such as unfavorable air flow, improper ventilation, lack of safe distancing and mask use, contaminated HVAC, and PM inducing and high impact verbal activities like singing (Almilaji, 2021; Amoatey et al., 2020; Katelaris et al., 2021; Kwon et al., 2020; Lu et al., 2020; Chau et al., 2021; Revollo et al., 2021; Groves et al., 2021; Ou et al., 2021).

In terms of worldwide research, Bangladesh and Central African Republic are the only least developed countries found to test indoor air for SARS-CoV-2 (Harries et al., 2020; Akter et al., 2021; United Nations Department of Economic and Social Affairs (UNDESA) 2021). India, Iran, China, Bosnia and Herzegovina, Brazil, Korea, Lebanon, Malaysia, Vietnam, Russia and Nigeria are the only developing countries found to test or speculate for indoor SARS-CoV-2 (Kwon et al., 2020; Adeniran et al., 2021; Alkalamouni et al., 2021; Bazzazpour et al. 2021; Chau et al., 2021; Dubey et al., 2021; Hu et al., 2020; Hwang et al., 2021; Nor et al., 2021; Noureddine et al., 2021; Passos et al. 2021; Pochtovyi et al., 2021; Salihefendic et al., 2021; World Bank, 2021).

5.2. Indoor air parameters for plausible existence of SARS-CoV-2

Studies have reported the following particle sizes carrying SARS-CoV-2 in indoor air: 0.1 μm (Meiss et al., 2021b); > 0.25 μm (Liu et al., 2020b); 0.25 - 1.0 μm (Liu et al., 2020b; Lednicky et al., 2021); > 4 µm and 1 µm - 4 µm (Chia et al., 2020). Lee (2020) estimated a particle size of 4.7 μm carrying SARS-CoV-2. Indoor NO_2, PM_1, $PM_{2.5}$ and PM_{10} may indicate potential presence, but do not directly represent SARS-CoV-2 (Bianconi et al., 2020; Li et al., 2020a; Baboli et al., 2021; Bazzazpour et al. 2021; Li et al., 2021a Meiss et al., 2021a; Nor et al., 2021). Similarly to SARS-CoV, approximate temperatures of 20 °C - 28 °C and relative humidity of 20% - 80% are reported to be optimal conditions for the presence of SARS-CoV-2, but do not directly lead to its transmission (Casanova et al., 2010; Spena et al., 2020; Baboli et al. 2021; Raines et al., 2021; Razzini et al., 2020). Aerosol deposition on fomites is also a plausible SARS-CoV-2 transmission route, similarly to SARS-CoV (Memish et al., 2014; Colaneri et al., 2020; Hirota, 2020; Orenes-Piñero et al., 2021). Research in spaces with adequate ventilation, less population, high mask use and social distancing protocols have shown lesser probability of SARS-CoV-2 detection (Di Carlo et al., 2020; Faridi et al., 2020).

5.3. Indoor air quality treatment strategies to reduce risk of SARS-CoV-2 transmission

Since presence and transmission SARS-CoV-2 in indoor air has been proven, it is important to review latest research regarding management strategies for the reduction of SARS-CoV-2 transmission.

The use of natural ventilation has been reported to reduce SARS-CoV-2 transmission (Xiao et al., 2020b). However, the sole use of natural ventilation was stated as a plausible reason for SARS-CoV transmission due to it leading to uncontrolled air flow and direction (Li et al., 2004; Meiss et al., 2021a). Therefore, a minimum ventilation rate is recommended to be achieved prior to use of natural ventilation (World Health Organization (WHO) 2021a). Examples of enhanced natural ventilation techniques include opening doors along with windows, placing fans near open windows and in higher areas of rooms, uninterrupted use of exhaust fans, improving stack effect of buildings for better air circulation and opening windows 15 min before and after occupancy (Gola et al., 2021). Additionally, controlled use of air filters and HVAC with natural ventilation is recommended (Curtius et al., 2021; Meiss et al., 2021b; World Health Organization (WHO) 2021a).

CO_2 levels represent quality of ventilation and may therefore determine SARS-CoV-2 risk levels (Lu et al., 2021; Meiss et al., 2021a; Peng and Jimenez, 2021). Hence, determination of safe indoor CO_2 levels is recommended and could be maintained to less than 700 ppm or close to outdoor levels of less than 450 ppm (Ahlawat et al., 2020; Di Gilio et al. 2021; Eykelbosh, 2021; Lu et al., 2021). CO_2 monitors have been suggested to be placed near windows or 2 metres away from individuals and open flames (Eykelbosh, 2021).

HVAC systems recirculate air, which may lead to accumulation and transportation of coronaviruses (Kim et al., 2007; Almilaji, 2021; Shen et al., 2020a; Jones et al., 2021; Li et al., 2021b; Moreno et al., 2021). Air conditioners without fresh air and exhaust duct systems and heater fans have been reported to increase SARS-CoV-2 infections due to droplet transportation between individuals (Kwon et al., 2020; Chu et al., 2021; Jones et al., 2021). Combining AC and natural ventilation has been suggested for fresher air exchange and comfortable temperatures (Singh and Dewan, 2020). Darvishi et al. (2021) reported 87% purification of outlet air from SARS-CoV-2 through centrifugal isolation in a hospital AC, which consists of a 90° and 20 cm diameter pipe with a 4 m/s flow rate. Additionally, exhaust outlets have been recommended to be placed 4 metres away from individuals (WHO, 2021a). Furthermore, Yu et al. (2020) proposed the use of nickel foam filters heated at 200 °C within ACs, as they have shown to destroy 99.8% of SARS-CoV-2 and produce ambient air temperatures. ACs have also been recommended to be placed at higher areas of rooms for better air mixing (Gołofit-Szymczak et al., 2019; Moses et al., 2020; WHO, 2021a). Vents and grills in HVAC systems have been suggested to be disinfected with 75% soap or alcohol and water, and through methods suggested by manufacturers and experts (Marcone, 2020; WHO, 2021a). As temperatures and relative humidity of condensers in HVAC systems range from 50 °C - 80 °C and 40% - 50%, respectively, waste heat has been suggested to disinfect exhaust air from SARS-CoV-2 (Rezaei et al., 2020). Minimum air flow and ventilation rates is recommended to be determined according to sizes, activities and maximum occupancies of indoor spaces, as this affects relative exposure to SARS-CoV-2 (Jones et al., 2021; Ou et al., 2021). Fan coil or split system units may allow for enhanced mixing of air, considering that minimum ventilation rate is achieved (World Health Organization (WHO) 2021a).

SARS-CoV-2 dedicated areas in hospitals have been recommended to maintain high air flow with extractor fans and devices and negative air pressure (World Health Organization (WHO) 2021a). Plastic door zippers have been suggested in cases where room separations are unavailable, disinfection of rooms before admitting new patients, and consideration of health and isolation standards within healthcare architecture could be beneficial (McDonald, 2020; Jin et al., 2021).

As the presence of indoor PM and NO_2 may indicate presence of SARS-CoV-2, this could be monitored with inexpensive sensors and reduced with air purifiers (Kaliszewski et al., 2020; Li et al., 2020a; Liu et al., 2021a; Peladarinos et al., 2021). High efficiency particulate air filters (HEPA) and fine filters have been reported to disinfect 83% and 54% SARS-CoV-2 containing aerosols, respectively, and have a high filtration efficiency for 0.3 µm - 10 µm particles (Zhang, 2020; Zhao et al., 2020a). Air purifiers with HEPA can be portable, are inexpensive for richer developing countries such as China, and have been recommended to be specially used in healthcare facilities (Lednicky et al., 2020; Yeo et al., 2020; Zhao et al., 2020a; Rodríguez et al., 2021; Settimo and Avino, 2021). Air filters have been recommended to be positioned to face less cleaner air, regularly disinfected or discarded with medical waste, replaced according to expert or manufacturer advice, and to be used with UV lamps, face masks and ventilation (Zhao et al., 2020b; Cilhoroz and DeRuisseau, 2021; Curtius et al., 2021; Feng et al., 2021b; Lindsley et al., 2021). HEPA filters could also be used for low-cost respirators amongst frontline workers and can function uninterruptedly for up to 8 h (Jayan et al., 2020). Concepts of the circular economy have also been adopted to develop indoor air filters with clay (Shishkin et al., 2021). However, this needs further research in relation to disinfection from SARS-CoV-2.

Spaces such as public transport, offices and schools, where social distancing is challenging, have been suggested to be exposed to UV-C radiation when they are empty, and has been recommended to be used with caution due its carcinogenic, irritative and ozone (O_3) producing properties (Ahlawat et al., 2020; García de Abajo et al., 2020; Ploydaeng et al., 2020; Sengillo et al., 2020; Jin et al., 2021). Deep UV radiation has been reported to disinfect indoor air from SARS-CoV-2 and UV-C has been reported to reduce SARS-CoV-2 replication (Inagaki et al., 2020; Biasin et al., 2021). Additionally, application of lubricating eye drops and refraining from direct UV exposure has been recommended (Sengillo et al., 2020). Low-cost germicidal UV-C bulbs have been suggested to be installed in higher areas of the room for better air mixing, as their irradiance ranging from 28 - 80 $\mu W\ cm^{-2}$ are likely to reduce 88% airborne SARS-CoV-2 transmissivity within 16 s (Beggs and Avital, 2020; Davidson, 2021; Nardell, 2021; Volchenkov, 2021). Even though UV is effective to disinfect indoor air from SARS-CoV-2, its application is recommended in all possible directions to reduce potential infectivity from shielded particles (Doughty et al., 2021; Hill et al., 2021). Furthermore, a preprint by Mahammedi and Mahammedi (2020) proposed a solar powered UV mobile disinfectant which can be individualised to specific regions and scales.

Although ozonation is an environmentally friendly, relatively inexpensive method, with larger concentrations being more effective for disinfection from SARS-CoV-2, its use is considered harmful to respiratory health (Alimohammadi and Naderi, 2020). Hence, its maximum exposure should be limited to 0.5 ppm, and it must be used with other disinfection procedures and health and safety protocols (Alimohammadi and Naderi, 2020; Grignani et al., 2020; Mazur-Panasiuk et al., 2021; Merks et al., 2021; Moreno et al., 2021; Yano et al., 2020). Ozone dosage of 1 ppm has been reported to disinfect indoor air from SARS-CoV-2 by 90% within an hour, in conditions of 25 °C and 60% - 80% relative humidity (Yano et al., 2020; Oyeyemi et al., 2020). Fumigation with 0.5 ppm and 160 $\mu g\ m^{-3}$ of O_3 has also been reported to disinfect surfaces and indoor air, respectively, from SARS-CoV-2 (Cao et al., 2021; Percivalle et al., 2021). Plant-based ionisers have also shown to produce O_3 which disinfect aerosols and may potentially reduce chances of SARS-CoV-2 transmission (Suwardi et al., 2021).

Filtered 95, surgical, polycotton and polyprop masks have shown lesser particle travel than masks without polymers (Chughtai et al., 2020; Fischer et al., 2020; Li et al., 2020b). However, since there is less access to medical grade masks, promoting correct ways of wearing protective masks made with two or three layers of cotton, along with face shields or disposable masks have been recommended (Arumuru et al., 2020; Aydin et al., 2020; Fischer et al., 2020; Missoni et al., 2021; Shen et al., 2020b; Li et al., 2020b; Brooks et al., 2021; Deng and Chen, 2021; Clapp et al., 2021; Tanisali et al., 2021). Quilt and Cotton 600 TPI are also recommended to construct safe and reusable masks for general use, but reduced filtration efficiency of cotton masks post daily wash has been found (Chughtai et al., 2020; Maher et al., 2020; Hartanto and Mayasari, 2021). Other reported high filtration materials include microfibers, shop towels, coffee filters and lycra cloths (Hao et al., 2021), however need wider testing. Additionally, disposable facial FFP3 masks for essential workers have been suggested to be coated with silver nanocluster/silica composite, which is a low-cost material (Balagna et al., 2013, Balagna et al., 20202020). It has been advised that healthcare workers must use N95 or medical grade masks which could be reused for 7–10 days after steaming for two hours as a low-cost decontamination method (Adeniran et al., 2021; Ma et al., 2020). Some solutions to normalize mask usage are implementation of mask rules, behavior interventions for disabled individuals, higher levels of scientific education, and positive social media and leader influence (Betsch et al., 2020; Tso and Cowling, 2020; ; Frank-Crawford et al., 2021; M et al., 2021; Stosic et al., 2021). Mask use has been recommended with social distancing, air purification and efficient ventilation (Cheng et al., 2021).

Social distancing has shown to decrease SARS-CoV-2 infections, hospitalisations and deaths (Matrajt and Leung, 2020). It has been reported that distancing of 2 m is inadequate (Setti et al., 2020c). Hence, it must be implemented with adequate ventilation, air purification, limiting number of individuals to certain time periods and use of masks, along with funding and education for digital transformations and architecture to support social distancing (Augenbraun et al., 2020; Dzisi and Dei, 2020; Sun and Zhai, 2020; Cilhoroz and DeRuisseau, 2021; Megahed and Ghoneim, 2021; Shrestha et al., 2021).

6. Solid waste

6.1. Solid waste as plausible route of transmission

COVID-19 has exposed the solid waste management sector to multiple challenges including impacts from increased infectious waste generation, mixing of infectious waste with general waste, suspension of recycling activities, increased plastic waste, lack of inventorisation on amount of household hazardous waste, discontinued formal/informal waste management services, lack of awareness, lack of PPE and insufficient treatment capacities (United Nations Environment Programme (UNEP) 2020a). One of the key concerns arising from COVID-19 is the risk of transmission via solid waste management (Nghiem et al., 2020). Solid waste materials containing droplets, body fluids, or blood from infected COVID-19 patients may be contaminated with viable SARS-CoV-2 and are typically generated by health care centers, laboratories, isolation and quarantine facilities, and households with asymptomatic or infected individuals (Nghiem et al., 2020; Sangkham, 2020; Capoor and Parida, 2021). Rise in solid waste additionally exacerbated this concern as numerous studies reported dramatic medical waste influx during COVID-19. For instance, Spain marked an increased rate of 350% in medical waste and the United States reported a drastic increase from 5 million tons per year to 2.5 million tons per month (Jacob et al., 2021; Liang et al. 2021). In Wuhan (China), the daily generation of medical waste exceeded the city's maximum incineration capacity of 49 tons/day to 240 tons due to COVID-19 pandemic (Torkashvand et al., 2021). The risk of infectivity from solid waste management is more acute for waste management sector in developing countries due to incapability of providing hygiene practices to waste handlers and sanitary disposal techniques (Nzediegwu and Chang, 2020; Acharya et al., 2021). In addition, only 4 million out of the 19 - 24 million people in the waste management and recycling sector are formally employed (World Bank, 2020). This is a critical issue as untrained, unprotected, and unaware waste workers and/or informal workers are more likely to be continuously exposed to high degrees of occupational hazards from waste management operations during COVID-19 and can mediate transmission to community (World Health Organization (WHO) 2020b; Das et al., 2021; Roy et al., 2021).

Currently, there is no evidence that direct, unprotected human contact during the handling of MSW and health care waste result in the transmission of the COVID-19 virus (Capoor and Parida 2021; Liu et al., 2021b). Plausible transmission pathways through solid waste management could include dermal exposure to surfaces contaminated with SARS-CoV-2 (fomite transmission) and direct exposure to contaminated bioaerosols originating from solid waste (Di Maria et al., 2020; Sharma et al., 2020; Iyer et al., 2021; Mohammad et al., 2021; Vaverková et al., 2020). A predominant factor, the longevity of SARS-CoV-2 on solid surfaces, that may support the fomite transmission via solid waste materials is extensively discussed in literature. Several research studies have confirmed the stability of SARS-CoV-2 on experimentally inoculated common objects including cardboards, plastics, steel, glass, PPE from several hours to days at room temperature that are widely encountered by healthcare workers and frontline waste workers (Table 2). These findings shed light on understanding the viral persistence of the same materials in solid waste (Al Huraimel et al., 2020). However, pertaining to the viral concentrations, some scientists have expressed laboratory studies as unrealistic and higher than those of droplets in real-life situations (Goldman, 2020). In addition, the persistence of SARS-CoV-2 on solid waste could be different under actual environmental conditions with respect to the one detected on isolated smooth surfaces and could be influenced by environmental and climatic conditions (temperature, humidity, solar radiation) (Di Maria et al., 2020). Direct exposure to contaminated bioaerosols may pose health hazards to waste workers by inhaling bioaerosol containing microbes (Carducci et al., 2013). The release of bioaerosol may be facilitated by various activities during waste collection, loading and unloading, transportation, sorting, shredding/ grinding, on-site and landfill compaction, coverage of MSW and flushing or aeration processes in the leachate treatment plant (Sharma et al., 2020; Vaverkova et al., 2020). Researchers have also postulated plausible secondary route of transmission from solid waste by improper landfill management (Anand et al., 2021b). Viruses could migrate from landfill waste with leachates into the soil and ground water posing environmental contamination especially in countries with un-engineered dumping is practiced (Anand et al., 2021b). However, data related to fate of SARS-CoV-2 or other coronaviruses in bioaerosols from solid waste management and landfill leachate is currently unavailable. In short, ambiguity exists in relation to the stability of SARS-CoV-2 virus during solid waste management phases and available information are largely inconclusive, which calls for the need of further investigations (Ugom, 2020).

Table 2
Persistance of SARS-COV-2 on solid surfaces.

Medium	Lifespan of SARS-CoV-2	Test conditions		Reference
		Temperature	Relative humidity	
Printing and tissue papers	3 h	22 °C	65%	Chin et al. (2020)
Treated wood and cloth	2 days			
Glass and banknote	4days			
Stainless steel and plastic	7 days			
Outer layer of a surgical mask	7 days			
Aerosol	3 h	21 to 23 °C	40%	Van Doremalen et al. (20200
Plastic	3days			
Stainless steel	3days			
Copper	8 h			
Cardboard	24 h			
Polystyrene plastic, aluminum, and glass	4 days	19 °C –21 °C	45%–55%	Pastorino et al. (2020)
Glass, stainless steel and both paper and polymer banknotes	28 days	20 °C	50%	Riddell et al. (2020)
Cotton	4 h	20 °C	35–40%	Kasloff et al. (2021)
Plastic	21 days			
Stainless steel	14 days			
Nitrile gloves	7 days			
Chemical resistant gloves	4 days			
N-95 and N-100 surface materials	21 days			
Cloth (35% cotton and 65% polyester)	3 days	4 °C	40–50%.	Harbourt et al. (2020)

Several studies reported higher prevalence of work-related pulmonary symptoms (cough, phlegm, wheezing and chronic bronchitis) and greater decrease in lung function in waste workers compared to the control population (Yang et al., 2001; Ray et al., 2005; Athanasiou et al., 2010; Jayakrishnan et al., 2013). Even though, there is no adequate analyses on infection rates among health care waste handlers from COVID-19, low-income countries have reported that sanitary employees worked during COVID-19 pandemic without standard safe operating procedures through prolonged working hours due to staff shortages (Rahman et al., 2020; Sakamoto et al., 2020; Wardani and Azizah, 2020; Yousefi et al., 2021).

6.2. Sars-CoV-2 in the solid waste stream

Experimental research on SARS-CoV-2 content in municipal solid waste and medical waste materials were sparsely available, despite several review articles postulating the risks of SARS-CoV-2 presence in solid waste based on prevalence of SARS-CoV-2 on solid surfaces under laboratory conditions (Mol and Caldas, 2020; Nghiem et al., 2020; Nzediegwu and Chang, 2020; Sharma et al., 2020). Di Maria et al. (2021) detected SARS -CoV -2 RNA on 15% of 1175 samples of solid waste such as plastic coffee cups, plastic glasses, beverage cans, and plastic bottles that contained saliva with a viral load ranging from 4.8×10^3 to 4.0×10^6 genome copies/swab. Pertaining to medical waste materials, SARS-CoV-2 RNA has been detected on outer surface of medical waste bags (Lv et al., 2021), surgical masks (Hu et al., 2020; Pasquarella et al., 2020; Dargahi et al., 2021), PPE of health care worker (Peyrony et al., 2020), used gloves (Ye et al., 2020), PPE of medical staff including aprons and face shields (Krambrich et al., 2021) and outer part of the N-95 masks (Dargahi et al., 2021). In the above studies, only Hu et al. (2020) and Krambrich et al. (2021) tested viral infectivity. Hu et al. (2020) isolated viable virus from the surgical mask of one critically ill patient. Whereas Krambrich et al. (2021) failed in isolating viruses from the samples.

Other viral genomes detected in solid waste include noroviruses, hepatitis B virus, poliovirus 3 and echovirus 2 in human tissue wastes, discarded needles and fecal matter in solid in municipal solid waste (MSW) and Ebola virus RNA in gloves (Cocchi et al., 1984; Walsh et al. 1987; Collins and Kennedy, 1992; Bausch et al., 2007; Park et al., 2009; Paintsil et al., 2010). Carducci et al. (2013) detected infective torque teno virus (TTV) and human adenovirus (HAdV) in bio aerosols of landfill, recycling plant air, incinerator and waste vehicles surfaces. The human immunodeficiency virus (HIV) and hepatitis viruses B and C are among the infective viruses that can be transmitted through healthcare waste (World Health Organization (WHO) 2005). Studies have shown high prevalence of Hepatitis B virus among waste management employees compared to the general public (Dounias et al., 2005; Squeri et al., 2006; Amsalu et al., 2016; Moghaddam et al., 2016). Pertaining to COVID-19, more investigations are needed to advocate appropriate precautionary principles, due to high infectivity of the SARS-CoV-2 virus and high viability on various surfaces under laboratory conditions (Di Maria et al., 2020; Al Huraimel et al., 2020; Krambrich et al., 2021; Liu et al., 2021b).

6.3. Strategies to reduce risk of SARS-CoV-2 transmission from solid waste

Response strategies adopted by various countries to combat transmission risks for solid waste collection, recycling and treatment during COVID-19 differed considerably (Di Maria et al., 2020; Ragazzi et al., 2020; Capoor and Parida, 2021; Das et al. 2021; Liang et al., 2021; Roy et al., 2021). Some countries introduced additional measures for solid waste management such as separate household collection for COVID-19 patients (Italy), incineration on the same day of collection (South Korea), temporary storage collection expansion (UK) and prioritization of COVID-19 care home waste collection (UK) (Department for Environment Food & Rural Affairs (DEFRA) 2020; Kulkarni and Anantharama, 2020; Capoor and Parida, 2021). While countries such as U.S, Sweden and France continued to advocate the regular strategies practiced in normal MSW management with special emphasis to protection measures (Acharya et al., 2021; Capoor and Parida, 2021; Liang et al., 2021; Roy et al., 2021). The different approaches in response plans may indicate the lack of adequate knowledge in the infection potential of SARS-CoV-2 from solid waste and could reflect the social and economic differences within the regions (Mol and Caldas, 2020; Liang et al., 2021; Di Maria et al., 2020). Currently, there is no evidence for additional disinfection of healthcare waste and no specific protocol for COVID-19 waste, beyond requirements for general medical waste and are not considered Category A infectious substances (Occupational Safety and Health Administration (OSHA) 2021; World Health Organization (WHO) 2020b). Based on existing studies, improper waste management failing to adhere to standard operating procedures for solid waste rooted from the flaws in the existing waste management systems, which is commonly observed in low resource settings and could be a critical aspect in this regard (United Nations Environment Programme (UNEP) 2020a). Inadequacy in legislations and policies, mechanization and automation, technical knowledge, infrastructure, staff, safety measures, awareness and monitoring were observed during the COVID-19 outbreak that could contribute to the anticipated risk of SARS-CoV-2 infectivity from solid waste sector (Oruonye and Ahmed, 2020; Adelodun et al., 2021; Acharya et al., 2021; Falih et al., 2021; Zand and Heir, 2021). Scarcity of financial support and technical knowledge for waste-management are the major bottlenecks for developing countries (Sharma et al., 2020; Acharya et al., 2021). Only just over half of the countries in the world have any form of legislation in place regarding healthcare waste management and only about a quarter have dedicated laws (Oruonye and Ahmed, 2020; Adelodun et al., 2021; Chand et al., 2021; Falih et al., 2021). Waste management systems are designed for steady state flow with low variations generally, particularly in low-middle income countries waste sector is largely ignored and untreated as an essential service due to political and economic constraints (Acharya et al., 2021; Faisal et al., 2021; Goswami et al., 2021). Due to the dramatic surge in solid waste quantities that may lead to high infectivity, priority must be given to the aspects of linking bio-disasters with disaster waste management planning which currently focus mainly on debris management (Sharma et al., 2020). A national healthcare waste management policy incorporating regional differences and variations in local capacity and socioeconomic conditions is required to mobilize political decision making and governmental efforts for successful implementation of the plans during pandemics (World Health Organization (WHO) 2014; Petrosino et al., 2021). Multisectoral cooperation and interaction at all levels must be encouraged by forming emergency waste management team to communicate the risks from waste management and enabling safe management of solid waste as conducted by China (Roy et al., 2021). Strategies to strengthen waste management sector by collaborating NGOs, waste management professionals, informal sector, private and public sector entities through innovative and sustainable circular economy models must be prioritized for long terms plans (Almulhim et al., 2021; Goswami et al., 2021). Policies for distribution of loans, grants or other support programs such as insurance cover and protective logistics can support local entrepreneurships including informal sector (Neumeyer et al., 2020; Sharma et al., 2020). Strengthening sanitary workforce by giving key worker status as done by UK and capacity building through permanent training about biosafety protocols for solid waste management must be executed (Goyal, 2017; Habib et al., 2018; Acharya et al., 2021). Additionally, strategies to reduce human interaction during work such as automation and ensuring safe distance between waste management workers must be arranged to reduce the risk of COVID-19 transmission (UNEP, 2020a). Due to large scale presence of infectious waste in MSW from home care of COVID-19 patients, the aspects of public participation and social responsibility in policy making is very important for COVID-19 waste. Improved public awareness is vital to encouraging community participation, therefore, governments must facilitate awareness on source segregation and proper storage using different means such as advertisements, campaigns, newspaper articles, social media and campaigns to directly reach out to the people (Sharma et al., 2020; United Nations Environment Programme (UNEP) 2020a). In Taiwan, the city government encouraged citizens to record and report evidence of mask littering acts to authorities for the cash reward of 30% of the fines issued to the offenders (Sangkham, 2020). Participatory with active citizen involvement is adoptable for developing countries to maintain operational and functional efficiency of monitoring systems, in order to resist the plausible community transmission from solid waste during pandemics.

7. Wastewater

7.1. Presence of SARS-CoV-2 in wastewater

It is important to assess the fate of SARS-CoV-2 in wastewater as it leads to health and safety concerns, especially in less developed regions (Kumar et al., 2021). WHO reported no evidence of live SARS-CoV-2 in wastewater (World Health Organization (WHO) 2020b). However, Wang et al. (2020a) detected live SARS-CoV-2 in stool samples from Chinese hospitals, which opens the wastewater pathway for SARS-CoV-2 as it may plausibly spread through drainage stacks (Wang et al., 2021). SARS-CoV-2 RNA has been detected globally, excluding Antarctica, within stool samples and areas with influent and treated wastewaters such as hospitals, aircrafts, cruises, sewage, rivers, ground water, dam water and public water fountains in a recreational area (Ahmed et al., 2020a, 2020b; Giraud-Billoud et al., 2021; Rimoldi et al., 2020; Sherchan et al., 2020; Wang et al., 2020a; Albastaki et al., 2021; Johnson et al., 2021; Kozer et al., 2021; Mahlknecht et al., 2021). Further research is needed to elucidate SARS-CoV-2 within recreational waters. Wang et al. (2005) reported approximate stability of SARS-CoV RNA at 4 °C and 20 °C, for 14 and 2 days, respectively, in hospital wastewater. Although SARS-CoV RNA is not infective, its detection is advised to consider its presence to implement effective management (Wurtzer et al., 2020; Giacobbo et al., 2021). For example, SARS-CoV-2 RNA detection in Brazilian pipes aided to update public health policies and monitor infection spread and SARS-CoV-2 RNA detection in plumbing cleanouts in an external USA university site which resulted in less than three SARS-CoV-2 infections (Gibas et al., 2021; Prado et al., 2021).

In terms of worldwide research, Bangladesh is the only least developed country found to detect SARS-CoV-2 RNA in wastewater (Ahmed et al., 2021; United Nations Department of Economic and Social Affairs (UNDESA) 2021). The only developing countries found to attempt SARS-CoV-2 detection in wastewater include Argentina, Brazil, China, India, Iran, Mexico, Pakistan, Qatar and Serbia (Kumar et al., 2020; Fongaro et al., 2021; Giraud-Billoud et al., 2021; Haque et al., 2021; Kolarević et al., 2021; Saththasivam et al., 2021; Tanhaei et al., 2021; World Bank, 2021; J. Zhou et al., 2021c). Research from Nepal, Chile and Turkey is not peer reviewed (Ampuero et al., 2020; Kocamemi et al., 2020; Napit et al., 2021).

7.2. Plausible mechanisms of COVID-19 transmission and severity via wastewater

Faecal-oral SARS-CoV-2 transmission is proposed as plausible, however, further investigation is needed to validate this (Wang et al., 2020a; Gwenzi, 2021). Transmission routes via buildings, water supplies, water pipes, sewage systems and recreational areas are researched, but not validated (Luo et al. 2020; Balaraman et al., 2021; Feng et al., 2021a; Kang et al., 2021; Kozer et al., 2021; Soltani et al., 2021). Similarly, SARS-CoV infections in a Hong Kong residential complex were reported due to malfunctioning soil vent pipes and dry drains (Hung, 2003; Hung et al., 2006). Hence, trap seal protection, pipe layout designs, exhaust fans for optimal ventilation in water-contact spaces, and non-bendable vertical drainage stacks were recommended for high rise buildings (Hung, 2003; Hung et al., 2006).

Coronado et al. (2021) detected SARS-CoV-2 RNA in irrigation water, however, did not predict the same for soil. Hence, SAR-CoV-2 is plausibly unlikely to be soil or food borne (González et al., 2021). However, Duan et al. (2003) found approximate stability of SARS-CoV strain CoV-P9 in soil and water for three days. Hence, further research regarding SARS-CoV-2 from irrigation waters is needed as this may impact food supply chains, agriculture dependent and food insecure nations (Qadir et al., 2010; Falkenberg et al., 2018; Kerr, 2020; Zidouemba et al., 2020). Furthermore, wastewater treatment prior to irrigation and the use of forecasting models to reduce agriculture risks could be recommended (Helmecke et al., 2020; Tingey-Holyoak and Pisaniello, 2020).

SARS-CoV-2 RNA was reported in rivers with poor sanitation (Guerrero-Latorre et al., 2020). Even though the potential of SARS-CoV-2 transmission, along with other coronaviruses in aquatic environments is unlikely (Maal-Bared et al., 2021; De Rijcke et al., 2021), Sala-Comorera et al. (2021a) reported higher stability of infectious (heated-inactivated) SARS-CoV-2 titres within sterilised river and seawater samples at 4 °C than at 20 °C with higher stability in river water. Similarly, Guo et al. (2021) addressed the hypothetical flow of SARS-CoV-2 from wastewater into sea and its higher longevity at low temperatures and suggested that it may potentially affecting marine animals. Mathavarajah et al. (2021) compared marine species susceptibility to SARS-CoV-2 and suggested that this may have adverse impacts on marine species that may be prone to SARS-CoV-2.

Furthermore, even though Guo et al. (2021) did not find SARS-CoV-2 infections from human exposure to sea water, they suggested that sewage containing SARS-CoV-2 may possibly contaminate sea water and other viruses may transfer to natural water bodies accessed by humans for recreational purposes. For example, rotavirus and norovirus were detected in a natural lagoon of Brazil, and norovirus and human adenovirus were detected in a catchment area of Singapore (Vieira et al., 2012; Vergara et al., 2016). Hence, further research is needed for recreational waters as there is a slight probability of infection risk is suggested even though chances of transmission is low (Mahlknecht et al., 2021). For protection from SARS-CoV-2 through recreational waters, precautionary COVID-19 measures such as chlorine disinfection (applicable to pools), safety closures and updates, water monitoring and testing, strict visitor tracking along with hygiene and protection rules, public monitoring and prevention of entry for vulnerable populations could be implemented (Aygün and Tüfekçi, 2020; Romano-Bertrand et al. 2020; Brown et al., 2021; Quadri and Padala, 2021; Sala-Comorera et al., 2021b).

7.3. Wastewater treatment and sanitation strategies to reduce risk of SARS-CoV-2 transmission

Even though the chances of SARS-CoV-2 transmission from wastewater is low, it is important to reduce potential chances of infection as different reservoirs and transmission pathways exist (Gwenzi, 2021; Jones et al., 2021). Tertiary and secondary wastewater treatment methods are effective for disinfection from SARS-CoV-2, in that order (Sherchan et al., 2021).

Chlorine disinfection has been solely recommended for environmental disinfection purposes and the consideration of residual chlorine is recommended (Abu Ali et al., 2021; Xiling et al., 2021). For example, Achak et al., 2021 and Zhang et al. (2020a) addressed China's hospital wastewater guidelines for urgent disinfection during the COVID-19 pandemic which requires addition of a minimum of 6.5 mg/L free chlorine for 1.5 h in wastewater, irrespective of pH levels. Additionally, Nasseri et al. (2021) suggested that free residual chlorine is effective for wastewater treatment plants disinfection from SARS-CoV-2.

Ozonation disinfects treated wastewater to undetectable SARS-CoV-2 levels, is inexpensive and has wide uses within consumption, agriculture, recreation and groundwater remediation (Echeverry Ibarra et al., 2008; Remondino and Valdenassi, 2018; Sofia, 2020; Volkoff et al. 2020). For example, a small ozone concentration of 0.6 ppm in water decreased SARS-CoV-2 infectivity within a minute while 1 mg/L reduced up to 81.4% of SARS-CoV-2 within up to 10 s (Inagaki et al., 2021; Martins et al., 2021).

Temperatures of 70 °C in untreated wastewater have reported to reduce 90% and 99% of live SARS-CoV-2 within approximately 2.2 and 4.5 min, respectively (Bivins et al., 2020). Developing countries like Nigeria commonly boil water prior to consumption (Abubakar, 2021). However, this may not always be possible due to contaminants which may not be solely eliminated by high temperatures (Windsor et al., 2019).

Nasseri et al. (2021) found that UV successfully disinfected Iranian wastewater treatment plants with SARS-CoV-2. However, well-maintained activated sludge processes may have enhanced disinfection effectivity, which may be expensive for other developing countries (Craggs et al., 2014; Arif et al., 2020; Nasseri et al. 2021; Serra-Compte et al., 2021). Additionally, temperatures higher than 40 °C are needed for UV through solar stills to effectively inactivate SARS-CoV-2 in wastewater (Parsa, 2021; Parsa et al., 2021).

Ferrate based tablets have been reported to eliminate SARS-CoV-2 RNA in wastewater (Butor Škulcová et al., 2021). Jiang et al. (2018) suggested that lower amounts of ferrates could be used for wastewater treatment with probable low operating costs. Further research is needed to highlight the use of effervescent ferrate(VI)-based tablets for disinfection from SARS-CoV-2 in developing countries.

An ACE2 receptor-modified microalgae is a biohybrid microrobot that was prepared with centrifuged algae incubated with ACE2 receptor (employed by SARS-CoV-2 S protein), and has been reported for 95% and 89% elimination efficiency for spike protein and SARS-CoV-2 pseudo virus, respectively, within wastewater (Hoffmann et al., 2020; Zhang et al., 2021b). However, biohybrid microrobots are new and may be expensive for implementation (Lin et al., 2021), and further research is needed. On the other hand, more than 90% bacterial viruses could be eliminated in high-rate algal ponds, which require low energy and higher CO_2 requirements, therefore may have low costs and require lesser land (Craggs et al., 2014; Young et al., 2017; Molazadeh et al., 2019; Espinosa et al., 2021). Furthermore, it was suggested that algal systems could replace chlorination (Lesimple et al., 2020; Zhang et al., 2020a). Therefore, further research for disinfection from SARS-CoV-2 through high-rate algal ponds may be beneficial.

Inadequate and unequal resource accessibility of COVID-19 practices within Water, Sanitation and Hygiene (WASH) interventions have been found (Maal-Bared et al., 2020; Mushi and Shao, 2020; Zvobgo and Do, 2020; Adams et al., 2021). For example, healthcare facilities in countries such as Ghana, Kenya and Zimbabwe have unmet requirements for clean drinking water, water supplies, incineration and hand hygiene technology, responsible waste disposal, well-lit and clean environments, unshared toilets, pit latrines, swift response levels, management plans and health worker safety for long term optimum safety during the COVID-19 pandemic (Maina et al., 2020; Ashinyo et al. 2021; Hirai et al., 2021). The Indonesian government reduced costs of clean water to encourage higher levels of hygiene practises (Parikh et al., 2020). Such financial offloading practises could imply higher access to WASH while strengthening governance and public health and safety during disease outbreaks (Howard et al., 2020; Zvobgo and Do, 2020). Additionally, it may be important to consider shared toilet and bathing spaces in countries like India and Indonesia, along with the presence of gender, seasonal and climatic limitations to water, especially during the COVID-19 pandemic (Mukherjee et al., 2020; Parikh et al. 2020; Adams et al., 2021). Additionally, the provision of emergency WASH kits which include masks, soap water, household disinfectants with sodium hypochlorite and written precautions for SARS-CoV-2 infected households, along with free soap distribution for low and middle-income households could be beneficial (Aziz et al., 2020; Howard et al., 2020). In addition to WASH inclusivity, public awareness through campaigns and community led total sanitation and safety awareness and implementation for individuals in contact with wastewater has been suggested as essential for potentially reduced SARS-CoV-2 transmission through wastewater (Pandey et al., 2021; Sunkari et al., 2021; Wang et al., 2021).

8. Conclusion

Continuous global reporting of deforestation has aggravated concerns of the recurrence of devastating pandemics similar to COVID-19. Direct linkages connecting COVID-19 with deforestation is unavailable; however, the established impacts of forest loss on other bat mediated disease outbreaks are presumed to be intrinsically related to COVID-19. Evidence for increased plausible and potentially interconnected SARS-CoV-2 transmissions routes have been reported in environments of outdoor and indoor air, solid waste and wastewater, however, further investigations are needed to elucidate its effects through these themes. As the quality of outdoor air could potentially worsen the susceptibility to SARS-CoV-2 infection, more countries must adopt robust regulations for indoor and outdoor air quality, which are weak globally. Increasingly reported epidemiological studies connecting air pollution and COVID-19 should follow standardized methodologies and include additional confounding factors such as individual exposures to clearly elucidate the impact of air pollution. The plausible transmission risk of SARS-CoV-2 in indoor air could be high due to its viable and RNA detection through unvalidated transmission routes, including HVAC systems, hence, reported strategies must be integrated for higher effectivity of reduced transmission. Emphasis to improving personal protection measures, infrastructure and strengthening legal enforcement of waste management activities is paramount in developing countries to remediate the emerging risks from handling infective waste influx from pandemics. The plausible transmission risk of SARS-CoV-2 from wastewater is low, however, the implementation of management strategies is crucial due to its detection through unvalidated transmission routes which may affect humans, soils and marine species. Hence, environmental management has a direct impact on the emergence, spread, infectivity and lethality of disease outbreaks, including SARS-CoV-2. Further research to determine transmission and implications of SARS-CoV-2 through all environmental medias is needed, including in developing and least developed countries, especially within solid waste and deforestation. Controlling potential SARS-CoV-2 transmission in regions with lower access to resources highlights the need for collective policies with measurable goals. Moreover, it is essential to educate public and professionals regarding strategies and policies to ease the reduction of SARS-CoV-2 transmission. According to the One Health Approach, environment management with prevention of negative impacts, is highly likely to reduce the spread of SARS-CoV-2 and future outbreaks, and therefore improve population health and economies.

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.

Acknowledgments

This work was supported by the Division of Consultancy, Research and Innovation (CRI), Sharjah Environment Company – Beeah.

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