IJVAR
International Journal of Veterinary and Animal Research
Journal homepage: https://ijvar.org/index.php/ijvar

Interplay of Environmental Factors in The COVID-19 Pandemic: Transmission, Dynamics and Implications

Israa M. A. Mohamed[1,2]

[1]*Department of Agricultural Engineering and Socio-Economics, Kobe University, Kobe city 657-8501, Japan.*
[2]*Department of Animal and Poultry Hygiene & Environmental Sanitation, Faculty of Veterinary Medicine, Assiut University, Assiut city 71526, Egypt.*

ARTICLE INFO

Received: 15/01/2025
Accepted: 13/10/2025

DOI: 10.5281/zenodo.18142388

Corresponding Author: israahygiene@gmail.com

Keywords

Air pollution
Fecal-oral transmission
Wastewater epidemiology
SARS-CoV-2 environmental persistence
Viral surveillance
Public health implications

Cite this article as: *Mohamed I.M.A. 2025. Interplay of Environmental Factors in the COVID-19 Pandemic: Transmission, Dynamics and Implications. International Journal of Veterinary and Animal Research, 8(2): 107-124. DOI: 10.5281/zenodo.18142388.*

ABSTRACT

This review paper critically examines the multifaceted relationship between environmental determinants and the transmission dynamics of severe respiratory syndrome coronavirus 2 (SARS-CoV-2), the virus responsible for coronavirus disease 2019 (COVID-19). Through an extensive analysis of existing literature, it elucidates the intriguing connections between air pollution, particularly particulate matter (PM), and the incidence and severity of COVID-19 cases worldwide. Particles within the aerosol size range, known as aerosolized particles, can remain suspended in the air for extended periods and be transported over distances, thereby contributing to infection clusters in confined spaces, poorly ventilated areas, and close-contact settings. Additionally, this review investigates the influence of weather conditions, including temperature, humidity, and solar radiation, on COVID-19 spread and severity, emphasizing the complex interplay of environmental factors in viral transmission. Furthermore, the presence of SARS-CoV-2 in water sources has raised questions about waterborne transmission. Studies have detected viral RNA in wastewater (WW), rivers, and sewage, highlighting the potential for fecal-oral transmission. The review also evaluates the utility of WW-based epidemiology as a tool for early detection and surveillance of COVID-19 outbreaks, despite existing challenges in standardizing detection methods and correlating viral levels with clinical cases. Soil is also being examined as a potential reservoir and transmission medium for SARS-CoV-2. Meanwhile, studies have identified the virus in soil samples, mainly in areas with heavy contamination from infected individuals or medical waste. As a result, understanding the transmission dynamics of SARS-CoV-2 through air, water, and soil is crucial for developing effective control strategies and preventive measures.

INTRODUCTION

Over the last two decades, the world has experienced three significant pandemics, with coronavirus disease 2019 (COVID-19) triggered by severe respiratory syndrome coronavirus 2 (SARS-CoV-2) emerging most recently, preceded by the SARS outbreak in 2003 and MERS in 2012. All three pandemics resulted from zoonotic transmission, emphasizing the persistent threat of diseases from animal sources (Ramadan Shaib, 2019). SARS-CoV-2 spreads rapidly through direct contact or respiratory droplets from speaking, sneezing, or coughing (Anand et al., 2021). As of March 17, 2024, the world health organization (WHO) recorded 774,954,393 confirmed COVID-19 cases worldwide, along with 7,040,264 reported deaths, with figures continuing to rise (WHO, 2024). In this context, it is crucial to keep in mind that other potential causes of virus dissemination include pollution (Bontempi, 2020), and meteorological and socioeconomic variables such as trade exchanges. Because of its worldwide spread, recurring outbreaks, high fatality rate, and rapid transmission among vulnerable populations, COVID-19 remains a significant public health threat (Shrestha et al., 2022). The pandemic has caused significant human casualties on a global scale and posed an unprecedented threat to the economy, ecosystem, and healthcare industry. Therefore, huge international scientific efforts are being made in a variety of fields to better understand the variables affecting the new coronavirus's transmission and infectiousness with the hopes of limiting its spread, slowing the rate of diffusion, and creating novel therapeutic interventions or vaccines (Lundstrom et al., 2023).

Understanding the behavior and dynamics of SARS-CoV-2 in the environment is essential for preventing future outbreaks. Healthy individuals are most commonly infected by inhaling virus particles released by infected individuals during everyday activities like speaking, sneezing, and coughing (Chatterjee et al., 2020). Jin et al. (2020) suggests that the primary mode of transmission for SARS-CoV-2 is through respiratory droplets (particles >5μm). In May 2021, the Centers for Disease Control and Prevention (CDC) updated its COVID-19 guidelines to acknowledge that aerosolized particles smaller than droplets can linger in indoor air for minutes to hours, increasing the risk of exposure. It's also important to consider that SARS-CoV-2 may spread via other routes beyond contaminated droplets (Morawska et al., 2009; Piscitelli et al., 2022a).Surfaces touched by infected individuals, as well as water, sewage, trash, or soil, can serve as channels for transmission (Gogoi et al., 2023; Onakpoya et al., 2021). However, the duration for which infectious virus particles can survive in airborne suspension is still debated. The risk of COVID-19 infection decreases as the distance from the source increases and as more time passes since exhalation. Heavier respiratory droplets carrying the virus fall to the ground or surfaces due to gravity, while smaller droplets and aerosols stay suspended in the air and disperse as they mix with larger volumes and flows of air (CDC, 2020, 2021). Environmental factors such as temperature, humidity, and UV radiation can also influence the degradation of viral particles over time (CDC, 2020, 2021). These elements may have a significant role in the developing seasonal pattern of the SARS-CoV-2 epidemic waves.

Meanwhile, several studies have indicated that SARS-CoV-2 can persist in the human gastrointestinal system, suggesting that human excreta may represent a new route of transmission for the virus (Machkovech et al., 2024). Notably, SARS-CoV-1 nucleic acids were detected in patient excreta and urine, remaining viable for 3 to 17 days (Parida et al., 2023). Hung et al. (2004) found up to 10^7 copies of SARS-CoV-2 RNA per milliliter of stool and 2.5 x 10^4 copies per milliliter of urine. Additionally, Xiao et al. (2020) reported that 39 of 73 hospitalized SARS-CoV-2-infected patients had positive stool samples, with 23.29% of them continuing to test positive for the virus even after viral RNA was no longer detectable in the respiratory tract. SARS-CoV-2 was also found in the stool of an asymptomatic child whose respiratory samples were negative for the virus (Tang et al., 2020a). A recent study examined the durability of different types of personal protective equipment (PPE) widely used by medical professionals and the general public during the pandemic (Kasloff et al., 2021). Their research showed that SARS-CoV-2 RNA could remain on various PPE for different lengths of time. For example, the virus was detectable on face shield plastic and N-95 masks for up to 21 days, while Tyvek, which is a synthetic material made from high-density polyethylene (HDPE) fibers maintained the virus for 14 days, nitrile gloves for 7 days, and cotton fabric for about 4 hours at 20°C and a relative humidity of 35% to 40%. These results suggest that the existing water infrastructure connected to hospitals, public spaces, homes, toilets, drains, runoff, and water treatment systems could play a role in the widespread transmission of the virus. The study highlights the importance of proper PPE management in high-risk settings and suggests using cotton-based materials, such as cotton masks, as they show lower viral persistence, potentially helping control the spread of COVID-19. Similar to how norovirus and rotavirus have been documented to spread through aerosolization during wastewater (WW) and sludge treatment (Pasalari et al., 2019), SARS-CoV-2 could also be transmitted through water-soil-food pathways. Therefore, further research is needed to evaluate the public health risks associated with the aerosolization of SARS-CoV-2-contaminated WW and the inhalation of infectious bioaerosols (Kanwar et al., 2023).While water and air have received considerable attention regarding SARS-CoV-2 transmission, soil as a potential secondary transmission route has been relatively understudied. Moreover, storm water runoff from agricultural regions can carry contaminants, including SARS-CoV-2, into surface or groundwater bodies (Kanwar et al., 2023). Continuous sewage discharge can also impact soil ecosystems, potentially serving as a reservoir for the virus and contributing to secondary transmission sources. To fully understand SARS-CoV-2 transmission, it is essential to investigate the interactions of various environmental factors, including air, water, soil, and food. Figure 1 illustrates potential pathways for the SARS-CoV-2 in water and soil environments, highlighting the need for continued research in this area.

This review aims to explore the unprecedented environmental impacts of the COVID-19 pandemic, drawing on a thorough synthesis of global data from multiple fields. The novelty lies in its examination of the intricate interactions between the virus and environmental factors, encompassing air quality, water quality, noise pollution, and greenhouse gas emissions. Furthermore, it aims to elucidate the pathways through which SARS-CoV-2 transmission is influenced by environmental conditions, paving the way for effective mitigation strategies. Through this endeavor, the review underscore the broader implications of the pandemic on environmental sustainability and advocate for transformative practices that prioritize both human health and ecological well-being.

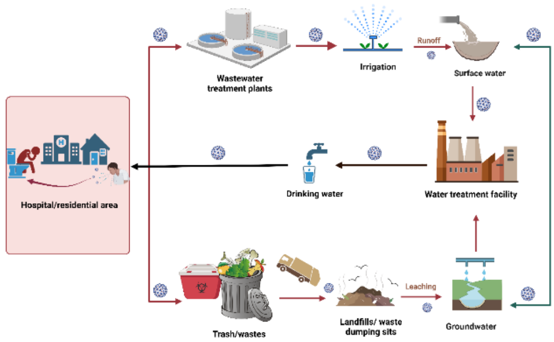

Figure 1. Potential pathways for SARS-CoV-2 transmission in aquatic and soil ecosystems.

ENVIRONMENTAL DETERMINANTS OF SARS-COV-2 TRANSMISSION

Research Group on COVID-19 and air pollution

Investigating the relationship with particulate matter: A growing body of evidence suggests an interesting connection between air pollution levels and the incidence of COVID-19. For instance, regions with elevated levels of particulate matter (PM) have reported higher rates of COVID-19 cases (Domingo and Rovira, 2020). Additionally, studies have detected SARS-CoV-2, the virus responsible for COVID-19, in outdoor air PM in urban areas of Northern Italy and the United States of America (USA) (Setti et al., 2020a). Furthermore, Linillos-Pradillo et al. (2021) examined the presence of SARS-CoV-2 RNA in outdoor air samples of PM-10, PM-2.5, and PM-1, using data collected between May 4 and May 22, 2020, in Madrid. The study employed MCV high-volume samplers with three inlets to gather samples using quartz fiber filters. The RNA extraction and amplification procedures were conducted following methods established by Setti et al. (2020) in Italy. The researchers concluded that the lack of detectable viral genomes could be due to several factors, including reduced social interactions, widespread mask usage, and economic restrictions, all of which likely helped curb the spread of the virus. Additionally, lower daily PM levels and rising temperatures during the spring season may have contributed to the observed findings.

Regarding the assessment of prolonged air pollution exposure and a potential rise in the severity of COVID-19 health effects, including mortality, Wu et al. (2020d) addressed the problems and outlined prospective paths and prospects. The same authors had previously noted that after adjusting for various area-level factors, higher historical exposures to PM-2.5 in the USA were associated with increased COVID-19 death rates at the county level (X. Wu et al., 2020e). However, the published study remains preliminary in assessing the impact of air pollution on the geographic spread of the disease, both locally and globally. Beyond any potential connection to COVID-19 transmission, there are many other compelling reasons to take strong action to reduce air pollution. The WHO 2021 report highlights that exposure to ambient air pollution is responsible for 4.2 million preventable deaths annually worldwide, along with numerous adverse health effects, including respiratory and cardiovascular diseases. In a study across 36 Organisation for Economic Co-operation and Development (OECD) countries, Barnett-Itzhaki and Levi (2021) examined the relationship between long-term, population-weighted exposure to PM-2.5 and NOx and the resulting morbidity and mortality over time following the first confirmed COVID-19 case. PM-2.5 levels were significantly associated with COVID-19 morbidity and mortality at 10, 20, 40, and 60 days, while NOx concentrations and population density correlated with these outcomes at 60 days. Continued exposure to air pollution above WHO guidelines may increase COVID-19 morbidity and mortality.

De Angelis et al. (2021) conducted an ecological study investigating the effects of prolonged exposure to PM and nitrogen dioxide (NO_2) on COVID-19 incidence and overall mortality. Their findings revealed a significant increase in COVID-19 cases as levels of PM-2.5 and PM-10 rose (58% and 34%, respectively). Additionally, a 10μg/m^3 annual increase in PM-2.5 was linked to a 23% increase in all-cause mortality. In contrast, NO_2 levels were negatively correlated with both COVID-19 incidence and all-cause mortality. Similar results were observed by Mele et al. (2021) and Gujral and Sinha (2021), who used separate neural networks to monitor these trends in Paris, Lyon, Marseille, Los Angeles, and Ventura. Moreover, Sangkham et al. (2021) conducted research in the Bangkok Metropolitan area, also highlighting the impact of air quality on viral dissemination. Evidence suggests that both short- and prolonged exposure to air pollution exacerbates respiratory disease symptoms and raises mortality rates, aligning with early investigations of COVID-19 death rates. However, these findings require further verification and support, considering individual-level risk factors (Piscitelli et al., 2022a). Zhu et al. (2021) highlighted the detrimental effects of PM on various aspects of human health, including the respiratory, circulatory, neurological, and immune systems, as well as their potential toxicological mechanisms. In addition, studies of the early COVID-19 outbreak in Northern Italy (Ho et al., 2021) and the Catalan Tarragona Province in Spain (Marquèsand Domingo, 2022) provided detailed accounts of the potential effects of both short- and long-term exposure to air pollution on COVID-19 risk and mortality rates. While there was notable county-level variability, Zhu et al. (2021) found compelling evidence that wildfires in the USA amplified the effects of short-term exposure to PM-2.5 on COVID-19 cases and fatalities.

Gaseous pollutants and COVID-19: A study conducted across 66 administrative districts in Italy, Spain, France, and Germany explored the relationship between COVID-19 and the distribution of tropospheric NO_2. The results revealed that 78% of the 4,443 death cases occurred in five regions of northern Italy and central Spain, which also had the highest NO_2 concentrations and downward airflow, impeding the effective dispersion of air pollution (Ogen, 2020). In another study, researchers examined the correlation between pollution levels of SO2, CO, NO_2, and ozone, and COVID-19 mortality. They found that a 10 μg/m^3 increase in NO_2 and ozone was associated with a 6.94% (95% CI: 2.38 to 11.51) and a 4.76% (95% CI: 1.99 to 7.52) rise in daily confirmed COVID-19 cases, respectively. Additionally, a 1 μg/m3 increase in CO levels corresponded to a 15.1% (95% CI: 0.44 to 29.77) increase in daily confirmed COVID-19 cases. Conversely, a 10 μg/m^3 increase in SO2 concentration was negatively correlated with COVID-19 cases, leading to a 7.79% decrease (95% CI: -14.57 to -1.01) in confirmed cases of the virus (Srivastava, 2021; Yang et al., 2020). These effects are illustrated in Figure 2.

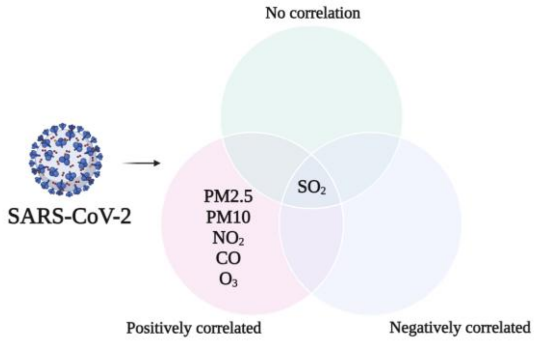

Figure2. Relationship between various pollution parameters with the number of COVID-19 cases

These findings suggest that both short- and long-term exposure to air pollution, including PM and gaseous pollutants, may increase COVID-19 transmission, severity, and mortality. Air pollution could act as a carrier for viral particles and exacerbate respiratory vulnerability, emphasizing the need for effective air quality management. Reducing emissions, improving urban ventilation, and enforcing pollution control measures could mitigate the health impacts of current and future respiratory viral outbreaks. Overall, these results highlight the critical role of environmental factors in shaping pandemic outcomes and the importance of integrating air pollution mitigation into public health strategies.

Weather conditions and COVID-19: Numerous studies, conducted worldwide, have shown that different climate characteristics, such as temperature, humidity, sunshine, etc., substantially impact the number of coronavirus cases and deaths (Table 1).

Table 1 Effect of various meteorological parameters on the number of COVID-19 cases and mortality

Parameter	Country	Relationship and result
Temperature	China (10 affected provinces)	Temperature and COVID-19 Asymmetric Nexus: Some trends are mixed, some indicate positive results, while a few show negative results (Shahzad et al., 2020)
	USA (New York)	Number of COVID-19 cases drastically declines as average and minimum temperatures rise (Bashir et al., 2020)
	China (Wuhan)	No evidence of a significant temperature increase to stop or delay the COVID-19 infections (Iqbal et al., 2020)
	Italy	A 1 ºF increase in daily temperature on average resulted in a 6.4 case reduction each day (Sobral et al., 2020)
	Iran	Temperature and COVID-19 do not significantly correlate (Ahmadi et al., 2020)
	China (17 different cities)	The drop in daily confirmed case numbers was correlated with an increase in ambient temperature of 1 °C (Liu et al., 2020)
	Turkey	The more COVID-19 cases there are on a given day, the lower the temperature is that day (Şahin, 2020)
	Indonesia (Jakarta)	The number of COVID-19 cases is highly correlated with temperature (Tosepu et al., 2020)
	China	The frequency of COVID-19 may be positively impacted by both lower and higher temperatures (Shi et al., 2020)
Humidity	USA (New York)	The number of instances or the overall number of cases is not greatly affected by average humidity (Bashir et al., 2020)
	Iran	Humidity and the rate of a virus outbreak are inversely related (Ahmadi et al., 2020)
	China (all provincial capitals)	Absolute humidity was highly correlated, and an increase in AH of 1 g/m3 was significantly linked to a reduction in the number of confirmed cases (Liu et al., 2020)
	Turkey	A rise in humidity is accompanied by a decline in the number of cases (Şahin, 2020)
	General	The COVID-19 morbidity and mortality are inversely associated with air humidity (Biktasheva, 2020; Martinez et al., 2020)
Rain Fall	USA	Rainfall and COVID-19 dissemination are inversely and sporadically connected (Bashir et al., 2020)
	Italy	Disease transmission increased after a rainstorm. There was an increase of 56.01 instances per day for every average inch per day (Sobral et al., 2020)
	Iran	There is no connection between the frequency of COVID-19 cases and rainfall (Ahmadi et al., 2020)
	Indonesia (Jakarta)	Rainfall and COVID-19 did not significantly correlate (Tosepu et al., 2020)
Wind speed	USA	Wind speed has a negligible impact on the dissemination of the virus (Bashir et al., 2020)
	Iran	Significant outbreak occurs at low wind speeds (Ahmadi et al., 2020)
	Turkey	More cases occur when the wind is blowing faster (Şahin, 2020)
Solar Radiation	Iran	Survival of the virus is threatened by solar radiation. Infection exposure rates were higher in regions with low sun radiation values (Ahmadi et al., 2020)

Temperature and COVID-19: Research aimed at establishing the link between temperature and COVID-19 cases yielded highly unusual results. The majority of the relationships were facility- and location-specific (Srivastava, 2021). There is an asymmetrical relationship between temperature and COVID-19, according to a study done in the top 10 impacted provinces of China. According to Shahzad et al. (2020), five of the 10 provinces showed mixed trends between temperature and COVID-19 instances, with three showing positive and two negative trends. Furthermore, the average and minimum temperatures were found to significantly correlate with COVID-19 instances in a different study carried out in New York (Bashir et al., 2020). An additional study conducted in Wuhan, China, disproves the findings of numerous other studies that suggested temperature played a key effect in limiting the spread of COVID-19. The findings did not support the idea that raising the temperature would help to contain or decrease COVID-19 infections (Iqbal et al., 2020). Meanwhile, in a different Italian investigation, it was discovered that a 1 ºF rise in the daily average temperature resulted in a 6.4 per day decrease in the number of cases. However, in some instances, COVID-19 mortality did not exhibit a statistically significant correlation with temperature (Ahmadi et al., 2020; Sobral et al., 2020). A previous study conducted across 17 Chinese cities found that an increase of 1°C in ambient temperature and the diurnal temperature range was linked to a decrease in the number of daily confirmed COVID-19 cases (Liu et al., 2020). In contrast, a study from Turkey suggested that on days with higher numbers of COVID-19 cases, temperatures were generally lower (Şahin, 2020). However, a study in Jakarta, Indonesia, found no significant correlation between temperature and the number of reported cases (Tosepu et al., 2020).

Humidity and COVID-19: Numerous studies conducted worldwide have highlighted the significant role that humidity plays in COVID-19-related morbidity and mortality. A study in New York found that average humidity had no effect on the overall number of cases (Bashir et al., 2020). Conversely, research in Iran indicated a negative correlation between humidity and the rate of virus outbreaks, although high virus transmission was observed in two humid regions of the country (Ahmadi et al., 2020). A study examining all of China's provincial capitals revealed that Absolute Humidity (AH) significantly reduced the number of confirmed cases in four cities. Additionally, a meta-analysis by Liu et al. (2020) showed that each 1 g/m3 increase in AH was notably associated with a decrease in confirmed cases. In Turkey, there was a strong correlation between humidity and daily case numbers, with the overall trend indicating that as humidity increased, the number of cases decreased (Şahin, 2020). Furthermore, another Chinese study found no correlation between COVID-19 frequency and AH (Shi et al., 2020). A notable study found that as of March 10, 2020, South Korea, Japan, Iran, and Northern Italy experienced the highest levels of Covid-19 community transmission. Despite varying relative humidity (ranging from 44% to 84%), these regions consistently showed low specific humidity (3–6 g/kg) and AH (4–7 g/m^3) levels (Sajadi et al., 2020).

Rainfall and COVID-19: There have been few studies examining the relationship between COVID-19 and rainfall. Bashir et al. (2020) conducted a study in the USA and found a sporadic and negative association between rainfall and disease spread, with higher transmission rates in areas experiencing more rainfall. Sobral et al. (2020) observed an increase of 56 cases per day for each inch of average daily rainfall. However, a separate study by Ahmadi et al. (2020) in Iran found no link between rainfall and COVID-19 cases. Similarly, research in Indonesia by Tosepu et al. (2020) also reported no significant relationship between rainfall and the spread of the virus.

Wind speed and COVID-19: Limited research has been conducted on the significance of wind speed in COVID-19 transmission. While generally not considered a significant factor, a study in the USA by Bashir et al. (2020) suggests that wind speed may have a modest yet noteworthy impact on virus spread. Conversely, an Iranian study by Ahmadi et al. (2020) found a notable increase in outbreaks during periods of low wind speed. Interestingly, a study in Turkey identified a strong correlation between the number of cases and average wind speed over 14 day (Şahin, 2020). It suggests that this timeframe is crucial for assessing correlations accurately, emphasizing the importance of considering wind speed over this duration when analysing COVID-19 transmission dynamics.

Solar radiation and COVID-19: Research on the connection between COVID-19 and solar radiation remains limited. An Iranian study suggested that solar radiation poses a threat to the virus's survival, with regions experiencing lower sun radiation exhibiting higher rates of illness exposure (Ahmadi et al., 2020). Figure 3 illustrates the relationship between different meteorological parameters and the number of COVID-19 cases.

The reviewed studies indicate that meteorological factors, including temperature, humidity, rainfall, wind speed, and solar radiation, may influence COVID-19 transmission, but the results are highly variable and location-specific. While some studies suggest higher temperatures and humidity reduce case numbers, others report no significant correlations, highlighting inconsistencies across regions and methodologies (Srivastava, 2021; Bashir et al., 2020; Şahin, 2020). Limited research on rainfall, wind speed, and solar radiation further complicates understanding of their roles in viral spread. These inconsistencies reveal critical research gaps, including the need for standardized, multi-location, longitudinal studies that account for confounding factors such as population density, human mobility, and public health interventions. Addressing these gaps would improve the predictive value of meteorological models and inform public health strategies for mitigating COVID-19 and other respiratory virus outbreaks under varying environmental conditions.

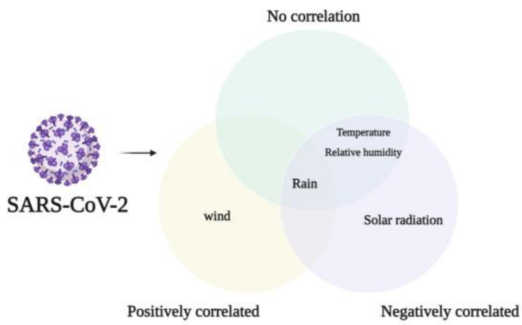

Figure 3. Relationship between various meteorological parameters with number of COVID-19 cases

Positive link between outdoor air pollution and COVID-19 incidence and severity

Recent continental and national studies: A variety of studies have been carried out globally, especially in countries heavily impacted by COVID-19, to explore how different air pollution factors influence mortality rates and case numbers related to the virus, as shown in Table 2.

Table 2. Overview of the findings from recent studies on the impact of air pollution on SARS-CoV-2 transmission and COVID-19 outcomes.

Study objectives	Key outcomes and summary	Reference
To investigate how PMs may have played a role in the COVID-19 outbreak in cities across Italy	An increase in COVID-19 infection is associated with both short-term and prolonged exposure to high amounts of contaminants. To confirm the varying susceptibility to infection between PM-exposed and unexposed cells, COVID-19 infection should be assessed with angiotensin-converting enzyme 2 (ACE2) expression after PM exposure.	(Comunian et al., 2020)
Exploring potential linkages: Air quality and SARS-CoV-2 spread in India's affected regions	In environments with moderate-to-high humidity, polluted conditions can increase the transmission rate of SARS-CoV-2.	(Manoj et al., 2020)
Impacts of air pollution on COVID-19 spread and mortality	The susceptibility to infection and mortality from COVID-19 may be increased by exposure to air pollution, particularly NO_2 dioxide and PM-2.5.The prognosis of individuals with SARS-CoV-2 infection can be negatively impacted by air pollution.	(Ali and Islam, 2020)
Studying the transmission and lethality of COVID-19 influenced by air pollution	Chronic air pollution exposure has a significant impact on the spread and fatality of COVID-19. Compared to PM-10, PM-2.5 and NO_2 had a stronger correlation with COVID-19.	(Copat et al., 2020)
Correlation between COVID-19 and ambient air pollution level	Exposure to PM may impair immune function and cause dysregulation, making it more difficult to fend off viral invasion. The invasion of the virus may be accelerated by ACE2 overexpression brought on by PM exposure. SARS-CoV-2 transmission distance may increase due to airborne PM.	(Wang et al., 2020a)
To calculate the percentage of COVID-19 deaths that can be attributed to exposure to ambient fine particle air pollution over a lengthy period	The risk of COVID-19 death is significantly increased by air pollution.	(Pozzer et al., 2020)
To provide a summary of SARS-CoV-2 transmission pathways	The research suggests that certain persistent factors influence the environmental behaviour and longevity of SARS-CoV-2. Outdoor risk factors, such as PM and aerosolized particles from wastewater treatment, should be closely examined because they may serve as carriers for the virus.	(Senatore et al., 2021)
How exposure to outdoor pollution may impact the pathogenesis of COVID-19 and the SARS-CoV-2 viral life cycle	PM, NO_2, and ozone exposure may increase the risk of COVID-19-associated immunopathology in exposed people by intensifying tissue inflammation and damage caused by the virus.	(Woodby et al., 2021)
Research from laboratory, animal, and human studies on how outdoor air pollution affects COVID-19	Air pollution exposure, both short-termand prolonged, may, through a variety of mechanisms, be a significant aggravating factor for the transmission of SARS-CoV-2 as well as the severity and fatality of COVID-19.	(Bourdrel et al., 2021)
Possible relationship between air pollution and COVID-19 mortality and occurrence	Air pollution, whether short-term or prolonged, may significantly contribute to the spread of SARS-CoV-2 through the air and could exacerbate the severity of COVID-19. Contact with NO_2 and PM-2.5 was linked to COVID-19 cases and deaths more often than exposure to PM-10.	(Ali et al., 2021b)
The part played and possible correlation between air pollution, particularly PM pollution, and the spread of COVID-19	The distribution of COVID-19 seems to be positively correlated with atmospheric PM pollution. According to certain research, PM acts as a carrier of viruses, encouraging their airborne spread. Population resistance to infection may be weakened by exposure to ambient PM.	(Maleki et al., 2021)
Potential COVID-19 transmission pathways and various virus mutations through environmental media	SARS-CoV-2 may be spread via PM. Further research concentrating on the virus's environmental transmission channels is necessary to help avoid and manage the COVID-19 pandemic.	(Shao et al., 2021)
The relationship between the frequency, prevalence, severity, and mortality of COVID-19 and acute and chronic exposure to air pollution	The most consistent contributors to COVID-19 include both short- and prolonged exposure to PM-2.5, as well as prolonged exposure to NO_2. ozone exposure seems to have a connection with the occurrence of new cases only. Research evaluating the consequences of acute exposures showed significant bias risks.	(Katoto et al., 2021)
To recap the function of PM in the transmission of COVID-19 and the connection between COVID-19, PM, and ACE2	There is scientific proof that PM levels and the SARS-CoV-2 spread are related. ACE2 is crucial to the COVID-19 pandemic.	(Khan et al., 2021)
COVID-19 is impacted by air pollution and climatic indices.	The rate at which COVID-19 cases spread and their severity are influenced by air pollution and meteorological factors. These processes may encompass several factors such as air pollution-induced comorbidities, damage to the respiratory system, increased pulmonary epithelial permeability, disruptions in immune and inflammatory responses, changes in metabolic pathways, and pollution-driven elevation of ACE-2 receptor expression.	(Zhao et al., 2021)

Table 2. (Continued).

Study objectives	Key outcomes and summary	Reference
Possible connections between PM and COVID-19 and several fatal human disorders	PM exposure may aid in COVID-19 transmission and SARS-CoV-2 spread. It is believed that oxidative damage and inflammatory responses are the main processes responsible for PM's detrimental effects.	(Zhu et al., 2021)
To examine the combined impact of SARS-CoV-2 transmission and ambient PM-2.5 exposure on worsening cardiopulmonary outcomes	Exposed patients to air pollution are more vulnerable to contracting COVID-19, which puts them in a pre-inflammatory state. Air pollution impacts cardiovascular and respiratory health, and the existence of respiratory and cardiovascular comorbidities affects COVID-19 mortality and prognosis. Chronic air pollution exposure increases inflammation, making certain populations more susceptible to contracting COVID-19	(Lai et al., 2021)
Explore the research on SARS-CoV-2 transmission during the COVID-19 pandemic, focusing on why airborne transmission has been less impactful from an environmental standpoint.	One reason for the reduced attention on airborne transmission could be the lower quantity of viruses in smaller droplets compared to larger ones. SARS-CoV-2 in small droplets might bind or mix with existing PM, thereby allowing PM composition to influence their behaviour and eventual outcome.	(Ram et al., 2021)

China: To explore potential links between environmental factors and COVID-19 cases and deaths in Wuhan and Xiao Gan, Li et al. (2020) investigated various weather elements, the air quality index (AQI), and four pollutants (PM-2.5, PM-10, CO, and NO_2). Their research suggests PM-2.5 and NO_2 may influence the spread of COVID-19 and found a correlation between disease frequency and temperature. In a similar study, Jiang et al. (2020) examined the potential links between air pollution, meteorological conditions, and daily COVID-19 case numbers in Wuhan, Xiao Gan, and Huan gang. The study focused on air pollutants such as PM-2.5, PM-10, SO_2, CO, NO_2, and ozone. The findings indicated that COVID-19 risk was associated with both humidity and PM-2.5 levels, while lower risks of COVID-19 were observed in relation to temperature and PM-10.

Lin et al. (2020) examined the influence of meteorological elements and air quality across mainland China to understand the factors significantly affecting SARS-CoV-2 transmissibility. From January 21, 2020, to April 3, 2020, they analyzed meteorological variables and levels of PM-2.5, PM-10, CO, SO_2, NO_2, and ozone, correlating them with the COVID-19 basic reproductive ratio. Their findings highlighted that higher ambient CO levels posed a risk for increased SARS-CoV-2 transmissibility in provinces with high flow, while higher temperatures, atmospheric air pressure, and effective ventilation lowered transmissibility. The impacts of meteorological variables and air pollutants varied regionally, with daily maximum temperature and 24-hour average NO_2 concentration inversely associated with the basic reproductive ratio. In contrast, X. Zhang et al. (2021b) conducted a study analyzing time series data from December 1, 2019, to April 6, 2020, to assess the correlation between daily confirmed COVID-19 cases and various environmental factors. Their research examined concentrations of PM-2.5, PM-10, CO, NO_2, SO_2, and ozone, alongside meteorological variables. The study revealed significant positive correlations between daily new confirmed cases and short-term exposure to PM-2.5, PM-10, and NO_2, indicating a strong link between air pollution and the spread of the virus.

Italy: Italy was one of the hardest-hit countries in Europe during the initial phase of the current pandemic. Consequently, many studies investigating the relationship between air pollution levels and the spread of COVID-19 have focused on Italy. For instance, Coccia (2020) conducted a study to identify factors contributing to the spread of COVID-19. They found a strong association between the rapid and widespread diffusion of COVID-19 in Northern Italy and air pollution levels in cities, particularly those beyond the limits set for ozone or PM-10. The study analyzed data from 55 district capitals in Italy, focusing on cases of infection up until April 7, 2020. In addition, Leonardo Setti et al. (2020a) examined 34 outdoor PM-10 samples collected from an industrial area in Bergamo Province, the epicenter of Italy's COVID-19 outbreaks, between February 21 and March 11, 2020. Their goal was to explore the potential role of PM in the spread of COVID-19 in Northern Italy. The findings suggested that SARS-CoV-2 could be present on outdoor PM, and that the virus might associate with PM-10 under stable meteorological conditions and high PM levels, thereby increasing its persistence in the atmosphere. In a subsequent study, Setti et al. (2020b) investigated whether air pollution could have a "boost effect" on the COVID-19 outbreak, potentially contributing to rare "super-spreader events." This Italian observational study, the first of its kind, examined the early spread of the virus across 110 provinces and found a significant relationship between daily PM-10 exceedances and the geographic spread of the virus.

However, Zoran et al. (2020) explored the link between surface air pollution and the high rates of SARS-CoV-2 infection, rapid spread, and mortality in the Milan metropolitan area. Their study, conducted from January to April 2020, investigated how common gaseous air pollutants like ozone and NO_2, along with weather factors, influenced the spread of SARS-CoV-2. They observed a positive link between air ozone levels and a negative link between NO_2 levels and the number of reported COVID-19 cases, daily new infections, and overall mortality rates. The researchers suggested that air pollutants might impact COVID-19 transmission and severity by causing respiratory issues and weakening the immune system. Zoran et al. (2020) also highlighted the significant influence of atmospheric PM-10 and PM-2.5 on the rise of COVID-19 cases in Milan. They suggested that exposure to these PM, in combination with potential bacterial or viral carriers, could impair the immune system, potentially exacerbating the spread and severity of COVID-19 cases. In the Lombardy region, Dragone et al. (2021) investigated the relationship between air pollution, alongside meteorological patterns, and the SARS-CoV-2 illness spread. Their findings suggested that both air pollution and climatic factors could potentially facilitate the spread of infectious virus particles. Similarly, Coccia (2021) analyzed statistical data from cities in Northern Italy, indicating support for the dynamic spread of SARS-CoV-2. Specifically, low wind speeds were identified as a potential factor prolonging the persistence of viral particles like SARS-CoV-2 in contaminated air. However, it's important to note that the spread of infectious diseases is influenced by various factors, making this conclusion tentative. On a related note, Accarino et al. (2021) examined the relationship between COVID-19 metrics (prevalence and mortality) and short-term exposure to PM-2.5, PM-10, and NO_2 during the first quarter of 2020. Their findings indicated that an increase in the number of days with PM-10, PM-2.5, and NO_2 levels surpassing annual limits was strongly correlated with higher COVID-19 prevalence, mortality, and lethality rates. In Italy, PM-2.5 and PM-10 had more substantial associations with these rates compared to NO_2. Similarly, Filippini et al. (2021) observed a positive, non-linear relationship between increased NO_2 levels in the troposphere and higher COVID-19 fatality rates in 16 provinces in Northern Italy that were heavily impacted by the pandemic

In contrast, De Angelis et al. (2021) employed an ecological approach to investigate the effects of prolonged exposure to PM-2.5, PM-10, and NO_2 on COVID-19 prevalence and all-cause mortality in Lombardy from March to April 2020. Their study, which accounted for demographic, social, and meteorological factors, found that a 10 $\mu g/m^3$ increase in the annual average levels of PM-2.5 and PM-10 from previous years correlated with a 58% and 34% increase in COVID-19 prevalence, respectively. Furthermore, a 10 $\mu g/m^3$ rise in annual PM-2.5 concentration was associated with a 23% increase in all-cause mortality. However, they observed an inverse relationship between NO_2levels and both COVID-19 prevalence and mortality. Stufano et al. (2021) also investigated the short-term association between air pollution and SARS-CoV-2 susceptibility in Lombardy, factoring in climate effects. They found that short-term exposure to ozone, PM-10, and PM-2.5 was linked to higher COVID-19 prevalence, but they concluded that air pollution and climate were not key drivers in SARS-CoV-2 transmission. This connection might reflect increased host susceptibility, potentially due to immune system vulnerabilities or exacerbated conditions tied to severe COVID-19 infections.

Additionally, Ho et al. (2021) investigated the impact of PM-2.5, PM-10, NO_2, SO_2, and ozone on COVID-19 incidence, mortality, and fatality rates, both short-term and prolonged, in Lombardy and Veneto over eight years (January 2013–May 2020). They found that exposure to SO_2 significantly contributed to the COVID-19 pandemic by causing systemic and respiratory inflammation. Other pollutants had effects similar to those reported in earlier Italian studies.

Studies from China and Italy have consistently shown positive associations between air pollutants—particularly PM-2.5, PM-10 and NO_2 and COVID-19 incidence and severity; however, these associations should be interpreted cautiously due to ecological study designs, limited time frames, and insufficient control for confounding factors such as meteorological conditions, mobility restrictions, and socioeconomic differences. Overall, the evidence suggests that air pollution may increase population susceptibility to respiratory infections rather than directly enhance viral transmission. Future studies should employ longitudinal or case-control designs with individual-level exposure assessments, high-resolution spatiotemporal modeling, and mechanistic analyses to clarify causality and inform targeted air-quality interventions for disease prevention.

Fecal-transmission of SARS-CoV-2

Viruses can be transmitted to humans through direct or indirect contact with contaminated fluids, such as surface water, food, and fomites (De Graaf et al., 2017; Radin; D. Xu et al., 2005). Another possible route of transmission is through feces, suggesting that SARS-CoV-2 may spread via this pathway as well (Figure 4). Recent data on COVID-19 has shown the presence of SARS-CoV-2 in the stool of affected patients. For example, an RT-PCR test conducted on a patient in Washington, USA, detected SARS-CoV-2 RNA in a stool sample taken on the seventh day of illness, even though serum samples tested negative (Holshue et al., 2020). Similar findings have been reported in other studies.(Y. Chen et al., 2020; Ling et al., 2020; A. N. Tang et al., 2020b; Y. Wu et al., 2020e; Yang et al., 2020; J. Zhang et al., 2020a; Y. Zhang et al., 2020b). Even after respiratory viral RNA tests negative, viral RNA can persist in feces for up to 33 day. Several studies have highlighted the potential for fecal transmission of SARS-CoV-2. For example, Ong et al. (2020) found that samples taken from a restroom used by a COVID-19-infected patient tested positive for the virus on surfaces such as the inside of the sink, the door handle, and the toilet bowl, even after cleaning, though post-cleaning samples tested negative. Similarly, van Doremalen et al. (2020) reported that viable virus particles could survive in aerosols for at least 3 hours and on plastic and stainless-steel surfaces for up to 2 or 3 days. Additionally, Zhang et al. (2020b) observed that the median duration of viral shedding in respiratory tract swabs was 10 days, while it could persist for up to 22 days in feces. Unhygienic environments, such as public restrooms, may promote the fecal-oral spread of the virus when individuals touch their mouth, nose, or eyes with contaminated hands (Ong et al., 2020; van Doremalen et al., 2020; Zhang et al., 2020b). However, the precise mechanism of SARS-CoV-2 transmission via the fecal-oral route remains uncertain (Xu et al., 2020), despite the prolonged shedding of the virus from the digestive system compared to the respiratory tract.

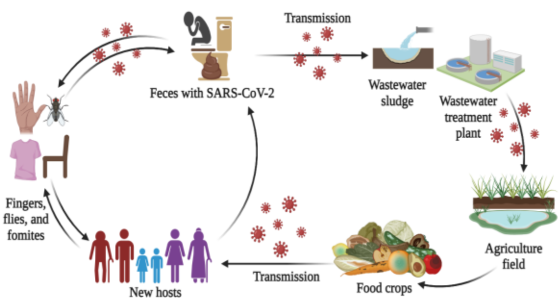

Figure 4. Fecal transmission of SARS-CoV-2.

Based on the research mentioned, while SARS-CoV-2 has been detected in the feces of infected individuals, there is no evidence supporting its presence in urine. Wang et al. (2020c) reported that no studies have confirmed the virus's presence in urine samples. Ling et al. (2020) suggested that

the rare transmission via urine or blood may be due to the low frequency of positive findings in patients.
Detection of SARS-CoV-2 RNA in fecal samples and on contaminated restroom surfaces indicates the potential for fecal-oral transmission; however, current evidence remains largely indirect and based on RNA detection rather than isolation of infectious viral particles. The prolonged presence of viral RNA in feces, even after respiratory samples test negative, suggests possible gastrointestinal persistence, yet the absence of consistent findings of viable virus limits definitive conclusions. Environmental studies demonstrating surface contamination and viral stability on fomites support the plausibility of this pathway, but do not confirm its epidemiological significance. To clarify this potential route, future research should focus on isolating infectious virus from fecal samples, assessing viral viability under varying environmental conditions (temperature, humidity, pH), and conducting epidemiological investigations linking sanitation infrastructure and wastewater exposure to infection risk. Standardized protocols for sampling, detection, and viability testing, along with experimental models assessing gastrointestinal infectivity, are essential to establish whether fecal-oral transmission contributes meaningfully to SARS-CoV-2 spread.

Presence of SARS-CoV-2 in WW sewage sludge, and surface water: Considering the initial reports of SARS-CoV-2 detection in feces (Holshue et al., 2020; Wölfel et al., 2020; Wu et al., 2020b), sewage should be recognized as a potential reservoir for a significant number of infectious virions. Various sources contribute to the presence of SARS-CoV-2 in household and hospital WW, including sputum, handwashing, and feces from infected individuals. Numerous studies, as listed in Table 3, have explored the presence of SARS-CoV-2 in river water, sewage, and sludge. However, it's important to note that some researchers have focused on detecting the virus rather than quantifying it. Additionally, reported virus levels are often expressed in different units, posing challenges for comparisons between studies. This underscores the need for standardized methods and units to facilitate meaningful comparisons in future research efforts.

In untreated WW, studies have reported varying rates of positive SARS-CoV-2 RNA detection, ranging from 13.3% to 100%, with concentrations in some cases exceeding 10^6 copies per liter. SARS-CoV-2 RNA has been consistently detected in WW in multiple studies. For example, in the Netherlands, the first detection of SARS-CoV-2 in sewage was reported, where 24-hour flow-dependent composite samples exhibited concentrations ranging from 2.6 x 10^3 to 2.2 x 10^6 copies per liter (Medema et al., 2020). The identification of SARS-CoV-2 RNA was carried out using reverse transcription-quantitative polymerase chain reaction (RT-qPCR) with CDC N1, N2, and N3 assays, and viral concentration was achieved through ultrafiltration. Similarly, in Massachusetts, United States, F. Wu et al. (2020b) reported SARS-CoV-2 loads ranging from 10^3 to 10^5 copies per liter in composite raw sewage samples, using ultracentrifugation and polyethylene glycol precipitation methods with a sample volume of 40 mL. In France, Wurtzer et al. (2020b) successfully recovered SARS-CoV-2 from WW samples using ultracentrifugation, with virus concentrations identified by the E gene RT-qPCR assay ranging from 5 x 10^4 to 3 x 10^6 copies per liter, showing a trend of increasing viral concentrations during the exponential rise in coronavirus cases.

Table 3. Occurrence of SARS-CoV-2 in sludge, WW, and river water.

Nation	Sample category	Positive sample rates, number (%)	Amount of SARS-CoV-2 (copies per liter)	Reference
Spain				
	Raw WW	4(66.7)	$7.5x10^3$- 15×10^3	(Balboa et al., 2020)
	Primary sludge	9(100)	10^4–4×10^4	
	Biological sludge	9(100)	7.5 x10^3-10 x10^3	
	Raw WW Secondary effluent	35(83.3) 2(11.1)	2.5×10^5	(Randazzo et al., 2020b)
	Raw WW	13(86.7)	5.22–5.99 $\log^{10}$	(Randazzo et al., 2020a)
Japan	Raw WW	7(25.9)	2.1x10^4 – 4.4×10^4	(Hata et al., 2020)
	WW	1(20)	1.4x10^2–2.5x10^3	(Haramoto et al., 2020)
Turkey	Raw sewage	5(71.4)	2.89x10^3–1.80x10^4	(Bilge Alpaslan et al., 2020b)
	Sewage sludge	9(100)	1.17x10^4 –4.02x10^4	(Bilge Alpaslan et al., 2020a)
USA	Raw WW	18(81.8)	Average 42.7×10^3	(Hyatt et al., 2020)
	Primary sludge	36(100)	1.7x10^6- 4.6×10^8	(Jordan et al., 2020)
	Raw WW	10(71.4)	10^4 – >2×10^5	(F. Wu et al., 2020a)
	Raw WW	7(100)	>3x10^4	(Nemudryi et al., 2020)
	Raw WW	2(13.3)	3.2 $\log_{10}$	(Sherchan et al., 2020)
	Raw WW	120(60.6)	10^2–10^5	(Gonzalez et al., 2020)
	Raw WW	126(61)	66–390	(Weidhaas et al., 2021)
Australia	Raw WW	2(22.2)	19–120	(Ahmed et al., 2020a)
France	Raw WW	23(100)	5x10^4–3x10^6	(S Wurtzer et al., 2020a)
Germany	Raw WW Secondary effluent	9(100) 4(100)	3.0 x10^3–20×10^3 2.7–37 x10^3	(Westhaus et al., 2021)
	Influent	44(86)	2.0 x10^3 –3.0×10^6	(Agrawal et al., 2021)
India	Raw WW	2(100)	0.78x10^2–8.05x10^2	(Kumar et al., 2020)
	Raw WW	30(100)	3.08 x10^4–2.19 x10^5	(Hemalatha et al., 2020)
	Raw WW	6(35.3)	N.A	(Sudipti et al., 2020)
Italy	Raw WW	6(50)	N.A	(La Rosa et al., 2020)
	Raw WW	4(50)	N.A	(Rimoldi et al., 2020)
	River waters	3(75)	N.A	

Table 3. (Continued).

Nation	Sample category	Positive sample rates, number (%)	Amount of SARS-CoV-2 (copies per liter)	Reference
Ecuador	River water	3(100)	$2.91x10^5$–$3.19x10^6$	(Guerrero-Latorre et al., 2020)
Netherlands	Raw WW	All*	N.A	(Lodder de Roda Husman, 2020)
	Sewage	14(58.3)	$2.6 x10^3$–$30 x10^3$ $7.9 x10^5$–$2.2 x10^6$	(Medema et al., 2020)
Pakistan	Raw WW	21(26.9)	N.A	(Salmaan et al., 2020)
Emirates	Raw WW	33(85)	$2.86x10^2$ –$2.9x10^4$	(Hasan et al., 2021)

N.A: not available

In Spain, Randazzo et al. (2020b) observed similar concentrations of SARS-CoV-2 RNA in untreated and treated WW samples using aluminum flocculation-based techniques and RT-qPCR assays (CDC N1–3), with levels estimated at approximately 2.5 x 10^5 copies per liter. This finding aligns with the research by Westhaus et al. (2021) in Germany, who employed centrifugal ultrafiltration and RT-qPCR targeting the M-gene or RNA-dependent RNA polymerase (RdRp). They reported SARS-CoV-2 RNA levels ranging from 3 x 10^3 to 2 x 10^4 copies per liter in influent and 2.7 x 10^3 to 3.7 x 10^3 copies per liter in effluent from 24-hour, flow-dependent composite samples. In Japan, Haramoto et al. (2020) detected SARS-CoV-2 RNA in secondary-treated WW samples using the electronegative membrane-vortex method and membrane adsorption-direct RNA extraction combined with the N_Sarbeco, CDC-N1, and CDC-N2 assays. Their results indicated approximately 2.5 x 10^3 copies per liter, about half the concentration reported by Randazzo et al. (2020b). In Australia, Ahmed et al. (2020a) used direct RNA extraction from electronegative membranes and ultrafiltration, detecting virus loads ranging from 120 to 19 copies per liter in grab samples and untreated WW composite. Despite the widespread use of WW surveillance for SARS-CoV-2 monitoring, there is a lack of research on the stability and survivability of the virus in water or WW (Tran et al., 2021). While most studies on SARS-CoV-2 quantification and detection in sewage have not investigated viral viability, some research, such as that by Rimoldi et al. (2020) and Wang et al. (2020b) has shown that the virus' infectivity in WW is nonexistent. Meanwhile, Westhaus et al. (2021) evaluated the infectivity of raw WW using a viral outgrowth test and found no infectivity.

In WW, SARS-CoV-2 concentrations are considerably lower than in feces, where levels can peak at 10^8 RNA copies per gram. This is due to significant dilution in the WW system, resulting in a 5-fold reduction in viral load (Foladori et al., 2020). The amount of SARS-CoV-2 in WW depends on the proportion of the population served by the sewer network who test positive for the virus, as well as on daily flow rates, which are estimated to dilute the viral load by approximately 1000 times. Additionally, factors such as rainfall can contribute further to the dilution process (Agrawal et al., 2021). Additionally, variations in pH, temperature, adsorption to solids, and settling, as well as differences in virus populations and infectivity, can occur along the sewer network (Foladori et al., 2020). The observed decrease in SARS-CoV-2 RNA levels in WW in Spain correlates with a decline in virus shedders within the community (Chavarria-Miró et al., 2020). Interestingly, a sudden drop in SARS-CoV-2 RNA in sewage was noted following a large rainfall event, which introduced a significant dilution factor to the virus concentration in WW (Chavarria-Miró et al., 2020). This highlights the importance of considering environmental factors, such as rainfall, when interpreting WW surveillance data. To accurately and reliably characterize the viral content in sewage, the method, timing, and volume of sample collection are crucial. Virus levels may fluctuate significantly throughout the day, making composite samples collected over time preferable and possibly advisable. (Foladori et al., 2020). Studies have found varying quantities of SARS-CoV-2 RNA in sludge, ranging from 7.5 x 10^3 to 4.6 x 10^8 copies/L. Primary sewage sludge was found to contain a range of 1.7 x 10^6 to 4.6 x 10^8 copies/L of SARS-CoV-2 RNA (Peccia et al., 2020). However, secondary and biologically treated sludge showed lower levels of contamination, with ranges of 10^4–4 x 10^4 copies/L and 7.5 x 10^3–10^4 copies/L, respectively (Balboa et al., 2020).These results align with a study by Kocamemi et al. (2020) in Turkey, where SARS-CoV-2 RNA was found in 9% of sludge samples. The detected viral RNA levels ranged from 1.17 x 10^4 to 4.02 x 10^4 copies/L Figure 5.

The inability to isolate infectious SARS-CoV-2 from water environments does not necessarily indicate its absence; rather, it may result from challenges in detection methods (Bogler et al., 2020). The lack of standardized and optimized techniques remains a significant obstacle to the detection and quantification of SARS-CoV-2 in WW samples. According to Ahmed et al. (2020a), the difficulties in isolating the virus from WW samples can be attributed to various factors, including the sampling method, low virus concentration, and the sensitivity of detection techniques, particularly when dealing with low virus levels. Additionally, factors present in WW, such as temperature, pH, solids, disinfectants, and micropollutants, can contribute to the degradation and inactivation of the SARS-CoV-2 genome, potentially leading to virus inactivation (Kitajima et al., 2020). While RT-PCR and RT-qPCR are widely used as the gold standard for SARS-CoV-2 detection, they cannot distinguish between infectious and inactive particles, necessitating the use of cell culture infectivity tests to assess virus viability. Overcoming these challenges is crucial for establishing standardized and reliable techniques for virus quantification and detection (Kitajima et al., 2020; Lodder and de Roda 2020; Tran et al., 2021). Recent research in Ecuador has identified the presence of SARS-CoV-2 RNA in rivers, with concentrations ranging from $2.91x10^5$ to $3.19x10^6$ copies/L. This suggests that contaminated natural water bodies could act as environmental reservoirs for coronaviruses such as SARS-CoV-2, highlighting the importance of taking strict measures to prevent re-infection (Danchin et al., 2020). Particularly in low-income nations with inadequate sanitary infrastructure, concerns about potential dispersion are significant (Guerrero-Latorre et al., 2020).

Despite the presence of bodily fluids with high viral loads, such as sputum and saliva, in greywater discharged from sinks, showers, and drains, it is not considered a primary route for SARS-CoV-2 transmission (Wang et al., 2020c; Wölfel et al., 2020). This may be due to the presence of disinfectants like detergents and soaps in greywater, which can reduce the persistence and infectivity of SARS-CoV-2 (Chin et al., 2020; Kampf et al., 2020). There is a growing need to evaluate the occurrence, persistence, and potential public health risks associated with SARS-CoV-2 in wastewater. Converging evidence could highlight the potential of wastewater-based epidemiology (WBE) to track the spread of SARS-CoV-2 within communities.

Figure 5. SARS-CoV-2 in sewage, sources, and eventual routes for spreading on soils, crops, and communities.

Epidemiological significance of monitoring SARS-CoV-2 in wastewater: The use of SARS-CoV-2 detection in WW as an early warning system to track current and future epidemic trends has gained significant attention, driving interest in WBE. Research has focused on the principles of this approach, with Orive et al. (2020) noting that changes in viral concentrations in WW can signal shifts in disease cases within human populations. This method involves measuring SARS-CoV-2 RNA markers in WW to monitor COVID-19 prevalence and gain insights into disease spread across communities (Holshue et al., 2020).

WBE employs a theoretical approach that begins with measuring the concentration of SARS-CoV-2 in municipal WW from a known urban area serviced by a sewer system. This concentration, expressed in copies per cubic meter, is then multiplied by the daily WW flow rate to calculate the daily viral load in copies per day. The daily viral load is compared with the viral copies found in the feces of individuals who tested positive for SARS-CoV-2, aiding in the estimation of the number of positive cases in the urban area (Foladori et al., 2020). Recent studies confirm the effectiveness of this method in monitoring COVID-19 spread. For instance, in Southeastern Virginia, variations in SARS-CoV-2 levels in WW correlated with documented outbreaks over 21 weeks (Gonzalez et al., 2020). Similar patterns have been observed in the Boston metropolitan area, as well as in the USA, Australia, France, and Spain, establishing a link between SARS-CoV-2 RNA levels in WW and clinical case surveillance (Ahmed et al., 2020a; Weidhaas et al., 2021; Wu et al., 2020c; Wurtzer et al., 2020b).

The study by F. Wu et al. (2020b) identified a notable discrepancy between COVID-19 prevalence estimates derived from WW analysis and clinical testing. While clinical tests reported a prevalence of 0.026%, viral levels detected in WW suggested a significantly higher estimate, ranging from 0.1% to 5%. Similarly, research conducted in Hyderabad, India, found that the estimated proportion of infected individuals (6.6%) exceeded the reported active cases (0.4%) (Hemalatha et al., 2020). This variation may be attributed to factors such as underreporting of asymptomatic or mildly symptomatic cases, constraints in testing capacity and accuracy, and delays between symptom onset and viral shedding (Hemalatha et al., 2020; Medema et al., 2020; F. Wu et al., 2020b).

Contrary to previous findings suggesting a threshold for detecting SARS-CoV-2 in WW, Hata et al. (2020) observed its presence even when confirmed cases were less than 1 per 100,000, aligning with Wurtzer et al. (2020a). Moreover, delays in clinical confirmation after symptom onset mean reported cases may not reflect the true infection frequency during the study period. The accuracy of WW monitoring is influenced by factors such as viral load in feces and the sensitivity of detection methods. Efficient virus concentration is crucial for the reliable detection of SARS-CoV-2 in WW. Recent studies (Medema et al., 2020; Nemudryi et al., 2020; Wu et al., 2020b; Wurtzer et al., 2020b) have explored various concentration techniques. Among these, Ahmed et al. (2020b) found that using an electronegative membrane combined with $MgCl_2$ pre-treatment was the most effective method for recovering SARS-CoV-2 from WW, using murine hepatitis virus as a surrogate. In contrast, Sherchan et al. (2020) demonstrated that the ultrafiltration method successfully retrieved SARS-CoV-2 RNA from untreated WW, while Jafferali et al. (2021) preferred the adsorption-elution technique with electronegative membranes. These differences highlight the need for further research to evaluate the effectiveness of existing virus concentration methods in accurately detecting and quantifying SARS-CoV-2 RNA in WW.

Various assays have been developed to detect SARS-CoV-2 by targeting genes encoding the nucleocapsid (N) protein, envelope (E) protein, and RNA-dependent RNA polymerase (RdRp), each with different detection limits. For instance, Corman et al. (2020) introduced a highly sensitive RT-qPCR assay targeting the N gene, capable of detecting as few as five RNA copies per reaction. The N gene is the most commonly used target in RT-qPCR tests (Corman et al., 2020; Shirato et al., 2020). Additionally, paper analytical devices (PADs) have gained attention for detecting viral nucleic acids due to their accuracy, simplicity, sensitivity, speed, and cost-effectiveness (Mao et al., 2020; Tran et al., 2021). These advantages make PADs a promising tool for SARS-CoV-2 detection in water environments (Orive et al., 2020; Mao et al., 2020; Tran et al., 2021). Still, most reports on WBE have focused on short-term studies (Orive et al., 2020).

While WBE approaches hold promise for monitoring COVID-19 outbreaks, systematic evaluation and forecasting of these outbreaks have yet to be established (Polo et al., 2020). The current lack of comprehensive data suggests caution in using them as routine surveillance methods for COVID-19 (Amahmid et al., 2022). Challenges arise in correlating viral levels in WW with clinically confirmed cases, given varied transmission patterns and geographic regions. Addressing these challenges will require further research, particularly in optimizing sampling methods and establishing standardized protocols for viral concentration and detection in WW (Ahmed et al., 2020b; Orive et al., 2020). Despite these limitations, WBE can serve as an early warning system for monitoring SARS-CoV-2 in surface waters. By monitoring river water at multiple locations near major sewage discharge sites, it becomes possible to detect potential increases in infection rates and subsequently control the spread of the virus (Amahmid et al., 2022; Núñez-Delgado, 2020). However, the full potential of this approach will depend on overcoming technical and logistical challenges and accumulating more robust data to validate its efficacy in real-world settings.

SARS-CoV-2 persistence in soil

Ensuring the health of plants, animals, and humans relies heavily on maintaining healthy soil conditions. Soil-transmitted pathogens, such as viruses, can persist in the soil for extended periods, posing a risk of transmission to hosts via soil particles (Amoah et al., 2017). Human enteroviruses, for instance, have been documented to survive up to 100 d in soil (Duboise et al., 1976; Ekanayake et al., 2023).However, while there has been extensive research on the persistence and transmission of viruses in water, studies examining SARS-CoV-2 persistence in soil environments remain limited.

The soil environment is exposed to various contaminants, including solid waste, sewage from wastewater treatment plants (WWTPs), biosolids from landfills, and airborne particles (Ekanayake et al., 2023). Studies indicate that applying sewage to soil may promote pathogen survival and transport, largely due to the high organic matter content of biosolids (Horswell et al., 2010). Studies have shown that municipal sewage sludge spreading on land can lead to the contamination of soil and water with enteroviruses, which may persist for up to 14 d in soil (Pourcher et al., 2007). Moreover, *Escherichia coli* bacteria have been found to survive for four weeks in leachate produced from laboratory-treated sludge (Ekanayake et al., 2023; Pousada-Ferradás et al., 2012). Recent studies have detected SARS-CoV-2 RNA in sewage sludge, raising concerns about potential soil contamination. Traces of the virus have been found in primary sludge from municipal WWTPs in New Haven, USA, as well as in waste-activated sludge from WWTPs in Istanbul (J. Peccia et al., 2020b). Furthermore, the presence of SARS-CoV-2 in both treated and untreated sludge suggests that conventional WW sludge treatment methods may not be entirely effective in eliminating the virus (Serra-Compte et al., 2021).

The presence of organic materials in sludge and the virus's hydrophobic nature may contribute to its affinity for sludge (Conde-Cid et al., 2021). Consequently, soil and crop plants may become contaminated in areas where sewage is used as a soil amendment, potentially leading to the contamination of food products (Núñez-Delgado, 2020). Direct release of disinfected solid waste, application of untreated WW for irrigation, and disposal of medical waste on land further contribute to soil contamination with SARS-CoV-2. In outdoor hospital environments, SARS-CoV-2 has been detected in soil samples, with counts ranging from 205 to 550 copies/g in areas close to hospitals and WW treatment facilities (Zhang et al., 2021). The detection of SARS-CoV-2 in soil samples within two meters of WW treatment tanks suggests that outdoor hospital environments should be regarded as high-risk areas, potentially acting as secondary transmission pathways. Additionally, the improper disposal of PPE equipment , such as face masks and gloves, without adequate decontamination increases the likelihood of viral migration into the soil (Ilyas et al., 2020).

Viable SARS-CoV-2 viruses have been shown to persist on solid waste surfaces, potentially heightening the risk of soil contamination (Li et al., 2020b). Research indicates that SARS-CoV-2 can survive in soil environments for over ten weeks under favorable conditions, highlighting the need to quantify the virus in soil to assess future risks of transmission. This approach is similar to WW surveillance, which serves as an important epidemiological tool for tracking viral spread (Ekanayake et al., 2023).

While there is limited evidence of SARS-CoV-2 infecting humans or spreading through food and soil, precautions should be taken to prevent its migration to other environmental compartments. WW should undergo thorough screening before being applied to soil to mitigate the risk of COVID-19 transmission. Additionally, the disposal of PPEP M equipment and medical waste on land without proper decontamination could increase the risk of soil contamination with SARS-CoV-2 (Ekanayake et al., 2023).

DISCUSSION, IMPLICATIONS, AND FUTURE PERSPECTIVES

The evidence accumulated to date demonstrates that the transmission dynamics of SARS-CoV-2 are influenced by a multifactorial interplay involving environmental, meteorological, and anthropogenic factors. Meteorological variables including temperature, humidity, rainfall, wind speed, and solar radiation have been investigated extensively for their role in shaping COVID-19 incidence. However, the findings remain inconsistent and highly location-specific. While some studies suggest that elevated temperatures and higher humidity may reduce viral transmission, others report weak or non-significant associations, reflecting heterogeneity in regional climatic conditions, population behaviors, and methodological approaches. For instance, research in China and Italy highlighted positive correlations between low ambient temperatures or specific humidity levels and higher COVID-19 cases, whereas studies in Indonesia and New York found negligible or mixed effects. These inconsistencies underscore the complexity of environmental determinants and indicate that meteorological factors alone cannot reliably predict SARS-CoV-2 spread.

Air pollution, particularly exposure to fine PM (PM-2.5, PM-10) and NO_2, has consistently been linked with increased COVID-19 incidence and severity. Evidence from China and Northern Italy indicates that populations exposed to higher levels of air pollutants exhibited elevated case numbers, mortality, and disease severity. The underlying mechanism is likely indirect: air pollutants may exacerbate respiratory and systemic inflammation, impair immune defense, and increase susceptibility to viral infections rather than directly promoting SARS-CoV-2 transmission. These findings reinforce the broader public health importance of environmental quality and air pollution control as complementary strategies in pandemic preparedness. Moreover, regional variations in pollutant types and concentrations highlight the necessity of contextualizing epidemiological analyses within local environmental and demographic settings.

WBE has emerged as a robust and non-invasive tool for monitoring SARS-CoV-2 prevalence at the community level. Detection of viral RNA in untreated and treated WW, primary and secondary sludge, and surface waters has provided valuable insights into infection dynamics, particularly for asymptomatic or untested individuals. Studies across multiple countries including the USA, Spain, Japan, Germany, and Australia have demonstrated that viral RNA concentrations in WW often precede clinically confirmed cases, making WBE an effective early warning system. However, SARS-CoV-2 RNA quantification in WW is subject to several limitations, including dilution from variable flow rates, temporal fluctuations in viral shedding, rainfall events, and the technical sensitivity of concentration and detection methods. While RNA detection is robust, the infectivity of SARS-CoV-2 in WW appears negligible in most studies, suggesting that WW is primarily a monitoring medium rather than a significant transmission route. Nonetheless, in low-income regions with insufficient sanitation infrastructure, the potential for environmental dissemination warrants careful attention.

Soil and sludge contamination represents an additional potential environmental reservoir for SARS-CoV-2. The persistence of viral RNA in WW sludge, coupled with its application to agricultural land or inadvertent release into the environment, raises concerns about indirect exposure pathways. Evidence suggests that SARS-CoV-2 can remain detectable in soil and sludge for extended periods, particularly in the presence of organic matter, moisture, and favorable physicochemical conditions. While direct transmission from soil to humans or through food remains unproven, improper management of sewage, sludge, and medical waste such as face masks and gloves may facilitate viral deposition in terrestrial ecosystems. These findings highlight the need for rigorous treatment of WW, decontamination protocols for medical waste, and consideration of soil as a potential environmental compartment in viral epidemiology.

The public health implications of these findings are substantial. Integrating environmental and meteorological monitoring with WBE provides a cost-effective and sensitive means of tracking infection dynamics in real time, particularly in regions with limited clinical testing capacity. Furthermore, monitoring air quality and environmental contamination can inform targeted interventions to reduce population susceptibility and prevent secondary exposure events. The potential role of WW and soil as reservoirs emphasizes the importance of robust sanitation infrastructure, proper sludge management, and environmental hygiene to mitigate indirect viral transmission.

Looking ahead, several key areas require attention to strengthen the utility of environmental surveillance in pandemic management. First, there is a critical need for standardized protocols for sampling, viral concentration, and detection in WW, sludge, and soil. Harmonization of methodologies including RT-qPCR targets, sample collection volumes, and timing will improve the comparability and reliability of findings. Second, longitudinal, multi-site studies incorporating diverse environmental, climatic, and demographic contexts are essential to disentangle confounding factors and elucidate causal relationships between environmental variables and SARS-CoV-2 transmission. Third, assessing viral viability, not just RNA presence, is crucial for accurately estimating infection risks associated with WW and environmental matrices. Fourth, integrative modeling approaches that combine meteorological data, air quality, WBE metrics, and epidemiological information can enhance outbreak forecasting and guide public health interventions. Finally, comprehensive risk mitigation strategies including advanced WW treatment, safe sludge management, and controlled disposal of medical waste are imperative to prevent environmental reservoirs from contributing to future outbreaks.

CONCLUSION

In conclusion, SARS-CoV-2 transmission is shaped by a complex, multifactorial interplay between environmental conditions, air quality, human behavior, and sanitation practices. While direct infectivity from environmental compartments such as wastewater or soil appears limited, these media serve as valuable surveillance tools that can provide early warnings and insights into infection prevalence. Addressing methodological gaps, standardizing detection techniques, and expanding longitudinal studies will be critical to fully realize the potential of environmental epidemiology. A holistic, integrated approach that combines meteorological monitoring, air quality assessment, WBE, and soil surveillance will not only enhance pandemic preparedness but also strengthen resilience against future respiratory viral outbreaks.

Acknowledgement

Conflict of Interest

The authors declare that they have no competing interests.

Authorship contributions

Concept: I.M.A.M. , Design: I.M.A.M., Literature Search: I.M.A.M., Writing: I.M.A.M.

Financial Support

This research received no grant from any funding agency/sector.

REFERENCES

Agrawal S, Orschler L, Lackner S. 2021. Long-term monitoring of SARS-CoV-2 RNA in wastewater of the Frankfurt metropolitan area in Southern Germany. Scientific reports, 11(1): 5372.

Ahmadi M, Sharifi A, Dorosti S, Ghoushchi SJ, Ghanbari N. 2020. Investigation of effective climatology parameters on COVID-19 outbreak in Iran. science of the total environment, 729: 138705.

Ahmed W, Angel N, Edson J, Bibby K, Bivins A, O'Brien JW, Choi PM, Kitajima M, Simpson SL, Li J. 2020a. First confirmed detection of SARS-CoV-2 in untreated wastewater in Australia: a proof of concept for the wastewater surveillance of COVID-19 in the community. Science of the total environment, 728: 138764.

Ahmed W, Bertsch PM, Bibby K, Haramoto E, Hewitt J, Huygens F, Gyawali P, Korajkic A, Riddell S, Sherchan SP. 2020b. Decay of SARS-CoV-2 and surrogate murine hepatitis virus RNA in untreated wastewater to inform application in wastewater-based epidemiology. Environmental research, 191: 110092.

Ali I, Ding T, Peng C, Naz I, Sun H, Li J, Liu J. 2021a. Micro- and nanoplastics in wastewater treatment plants: Occurrence, removal, fate, impacts and remediation technologies – A critical review. Chemical engineering journal, 423: 130205.

Ali N, Fariha KA, Islam F, Mishu MA, Mohanto NC, Hosen MJ, Hossain K. 2021b. Exposure to air pollution and COVID-19 severity: A review of current insights, management, and challenges. Integrated environmental assessment and management, 17(6): 1114–1122.

Ali N, Islam F. 2020. The effects of air pollution on COVID-19 infection and mortality—A review on recent evidence. Frontiers in public health, 8: 580057.

Amahmid O, El Guamri Y, Rakibi Y, Ouizat S, Yazidi M, Razoki B, Kaid Rassou K, Asmama S, Bouhoum K, Belghyti D. 2022. Occurrence of SARS-CoV-2 in excreta, sewage, and environment: epidemiological significance and potential risks. International journal of environmental health research, 32(8): 1686–1706.

Amoah ID, Singh G, Stenström TA, Reddy P. 2017. Detection and quantification of soil-transmitted helminths in environmental samples: A review of current state-of-the-art and future perspectives. Acta tropica, 169: 187–201.

Anand U, Bianco F, Suresh S, Tripathi V, Núñez-Delgado A, Race M. 2021. SARS-CoV-2 and other viruses in soil: An environmental outlook. Environmental research, 198: 111297.

Azuma K, Kagi N, Kim H, Hayashi M. 2020. Impact of climate and ambient air pollution on the epidemic growth during COVID-19 outbreak in Japan. Environmental research, 190: 110042.

Balboa S, Mauricio-Iglesias M, Rodríguez S, Martínez-Lamas L, Vasallo FJ, Regueiro B, Lema JM. 2020. The fate of SARS-CoV-2 in wastewater treatment plants points out the sludge line as a suitable spot for incidence monitoring.

Bashir MF, Ma B, Komal B, Bashir MA, Tan D, Bashir M. 2020. Correlation between climate indicators and COVID-19 pandemic in New York, USA. Science of the total environment, 728: 138835.

Ben Maatoug A, Triki MB, Fazel H. 2021. How do air pollution and meteorological parameters contribute to the spread of COVID-19 in Saudi Arabia? Environmental Science and Pollution Research, 28: 44132–44139.

Biktasheva IV. 2020. Role of a habitat's air humidity in Covid-19 mortality. Science of the total environment, 736: 138763.

Bilge Alpaslan K, Halil K, Ahmet S, Fahriye S, Ahmet Mete S, Bekir P. 2020a. SARS-CoV-2 detection in Istanbul wastewater treatment plant sludges. medRxiv: 2020.05.12.20099358.

Bilge Alpaslan K, Halil K, Sabri H, Cevdet Y, Ahmet Mete S, Bekir P. 2020b. First dataset on SARS-CoV-2 detection for Istanbul wastewaters in Turkey. medRxiv: 2020.05.03.20089417.

Bontempi E. 2020. First data analysis about possible COVID-19 virus airborne diffusion due to air particulate matter (PM): the case of Lombardy (Italy). Environmental research, 186: 109639.

Bourdrel T, Annesi-Maesano I, Alahmad B, Maesano CN, Bind M-A. 2021. The impact of outdoor air pollution on COVID-19: a review of evidence from in vitro, animal, and human studies. European respiratory review, 30(159).

CDC. 2020. National Center for Immunization and Respiratory Diseases (NCIRD), Division of Viral Diseases. CDC COVID-19 Science Briefs. Centers for Disease Control and Prevention (US, Atlanta, GA). Scientific Brief: SARS-CoV-2 Transmission [Updated 2021 May 7]. Available from: https://www.ncbi.nlm.nih.gov/books/N.

CDC. 2021. Science Brief: SARS-CoV-2 and Surface (Fomite) Transmission for Indoor Community Environments. In CDC COVID-19 Science Briefs [Internet]. Centers for disease control and prevention (US).

Chakrabarty RK, Beeler P, Liu P, Goswami S, Harvey RD, Pervez S, van Donkelaar A, Martin RV. 2021. Ambient PM2.5 exposure and rapid spread of COVID-19 in the United States. Science of the total environment, 760: 143391.

Chen Y, Chen L, Deng Q, Zhang G, Wu K, Ni L, Yang Y, Liu B, Wang W, Wei C, Yang J, Ye G, Cheng Z. 2020. The presence of SARS-CoV-2 RNA in the feces of COVID-19 patients. Journal of medical virology, 92(7): 833–840.

Chen Z, Wei W, Liu X, Ni B-J. 2022. Emerging electrochemical techniques for identifying and removing micro/nanoplastics in urban waters. Water research, 221: 118846.

Chua MH, Cheng W, Goh SS, Kong J, Li B, Lim JYC, Mao L, Wang S, Xue K, Yang L, Ye E, Zhang K, Cheong WCD, Tan BH, Li Z, Tan BH, Loh XJ. 2020. Face masks in the new COVID-19 normal: materials, testing, and perspectives. Research, 2020.

Coccia M. 2020. Factors determining the diffusion of COVID-19 and suggested strategy to prevent future accelerated viral infectivity similar to COVID. Science of the total environment, 729: 138474.

Coccia M. 2021. How do low wind speeds and high levels of air pollution support the spread of COVID-19? Atmospheric pollution research, 12(1): 437–445.

Comunian S, Dongo D, Milani C, Palestini P. 2020. Air pollution and COVID-19: The role of particulate matter in the spread and increase of COVID-19's morbidity and mortality. International Journal of Environmental research and public health, 17(12).

Conde-Cid M, Arias-Estévez M, Núñez-Delgado A. 2021. SARS-CoV-2 and other pathogens could be determined in liquid samples from soils. Environmental pollution, 273: 116445.

Copat C, Cristaldi A, Fiore M, Grasso A, Zuccarello P, Santo Signorelli S, Conti GO, Ferrante M. 2020. The role of air pollution (PM and NO2) in COVID-19 spread and lethality: a systematic review. Environmental research, 191: 110129.

Danchin A, Ng TW, Turinici G. 2020. A new transmission route for the propagation of the SARS-CoV-2 coronavirus. Biology, 10(1): 10.

Das AK, Islam MN, Billah MM, Sarker A. 2021. COVID-19 pandemic and healthcare solid waste management strategy – A mini-review. Science of the total environment, 778: 146220.

Di Gilio A, Palmisani J, Pulimeno M, Cerino F, Cacace M, Miani A, de Gennaro G. 2021. CO2 concentration monitoring inside educational buildings as a strategic tool to reduce the risk of Sars-CoV-2 airborne transmission. Environmental research, 202: 111560.

Domingo JL, Rovira J. 2020. Effects of air pollutants on the transmission and severity of respiratory viral infections. Environmental research, 187: 109650.

Dragone R, Licciardi G, Grasso G, Del Gaudio C, Chanussot J. 2021. Analysis of the chemical and physical environmental aspects that promoted the spread of SARS-CoV-2 in the Lombard area. International Journal of Environmental Research and Public Health, 18(3): 1226. Available from: https://www.mdpi.com/1660-4601/18/3/1226.

Duboise SM, Moore BE, Sagik BP. 1976. Poliovirus survival and movement in a sandy forest soil. Applied and environmental microbiology, 31(4): 536–543.

Ekanayake A, Rajapaksha AU, Hewawasam C, Anand U, Bontempi E, Kurwadkar S, Biswas JK, Vithanage M.

2023. Environmental challenges of COVID-19 pandemic: resilience and sustainability – A review. EnvironmentalResearch, 216: 114496.

Foladori P, Cutrupi F, Segata N, Manara S, Pinto F, Malpei F, Bruni L, La Rosa G. 2020. SARS-CoV-2 from faeces to wastewater treatment: What do we know? A review. Science of the total environment, 743: 140444.

Gogoi B, Chowdhury NK, Shyam S, Choudhury R, Chetia M, Basumatary T, Sarma H. 2023. SARS-CoV-2 and other pathogenic organisms in food and water: health implications and environmental risk. In One Health: human, animal, and environment triad, 389–410.

Gonçalves SdO, Luz TMd, Silva AM, de Souza SS, Montalvão MF, Guimarães ATB, Ahmed MAI, Araújo APdC, Karthi S, Malafaia G. 2022. Can spike fragments of SARS-CoV-2 induce genomic instability and DNA damage in the guppy, Poecilia reticulata? An unexpected effect of the COVID-19 pandemic. Science of the total environment, 825: 153988.

Gonzalez R, Curtis K, Bivins A, Bibby K, Weir MH, Yetka K, Thompson H, Keeling D, Mitchell J, Gonzalez D. 2020. COVID-19 surveillance in Southeastern Virginia using wastewater-based epidemiology. Water research, 186: 116296.

Guerrero-Latorre L, Ballesteros I, Villacrés-Granda I, Granda MG, Freire-Paspuel B, Ríos-Touma B. 2020. SARS-CoV-2 in river water: Implications in low sanitation countries. Science of the total environment, 743: 140832.

Gupta B, Ambekar RS, Tromer RM, Ghosal PS, Sinha R, Majumder A, Kumbhakar P, Ajayan PM, Galvao DS, Gupta AK. 2021. Development of a schwarzite-based moving bed 3D printed water treatment system for nanoplastic remediation. RSC Advances, 11(32): 19788–19796.

Haramoto E, Malla B, Thakali O, Kitajima M. 2020. First environmental surveillance for the presence of SARS-CoV-2 RNA in wastewater and river water in Japan. Science of the total environment, 737: 140405.

Hasan SW, Ibrahim Y, Daou M, Kannout H, Jan N, Lopes A, Alsafar H, Yousef AF. 2021. Detection and quantification of SARS-CoV-2 RNA in wastewater and treated effluents: Surveillance of COVID-19 epidemic in the United Arab Emirates. Science of the total environment, 764: 142929.

Hata A, Honda R, Hara-Yamamura H, Meuchi Y. 2020. Identification of SARS-CoV-2 in wastewater in Japan by multiple molecular assays - implication for wastewater-based epidemiology (WBE). medRxiv: 2020-2006.

Hemalatha M, Kiran U, Kuncha SK, Kopperi H, Gokulan CG, Mohan SV, Mishra RK. 2020. Comprehensive surveillance of SARS-CoV-2 spread using wastewater-based epidemiology studies. medRxiv: 2020-2008.

Ho CC, Hung SC, Ho WC. 2021. Effects of short- and long-term exposure to atmospheric pollution on COVID-19 risk and fatality: analysis of the first epidemic wave in northern Italy. Environmental research, 199: 111293.

Hoang T, Nguyen TQ, Tran TTA. 2021. Short-term exposure to ambient air pollution in association with COVID-19 of two clusters in South Korea. Tropical medicine & ınternational health, 26(4): 478–491.

Holshue ML, DeBolt C, Lindquist S, Lofy KH, Wiesman J, Bruce H, Spitters C, Ericson K, Wilkerson S, Tural A. 2020. First case of 2019 novel coronavirus in the United States. New england journal of medicine, 382(10): 929–936.

Horswell J, Hewitt J, Prosser J, Van Schaik A, Croucher D, Macdonald C, Burford P, Susarla P, Bickers P, Speir T. 2010. Mobility and survival of Salmonella Typhimurium and human adenovirus from spiked sewage sludge applied to soil columns. Journal of applied microbiology, 108(1): 104–114.

Hyatt G, Maxwell W, Mary C, Ariana F, Karen G, Brittany LK, Teng Z, Frank AM, David AL. 2020. Quantification of SARS-CoV-2 and cross-assembly phage (crAssphage) from wastewater to monitor coronavirus transmission within communities. medRxiv: 2020.2005.2021.20109181.

Ilyas S, Srivastava RR, Kim H. 2020. Disinfection technology and strategies for COVID-19 hospital and bio-medical waste management. Science of the total environment, 749: 141652.

Iqbal N, Fareed Z, Shahzad F, He X, Shahzad U, Lina M. 2020. The nexus between COVID-19, temperature and exchange rate in Wuhan city: new findings from partial and multiple wavelet coherence. Science of the total environment, 729: 138916.

Jordan P, Alessandro Z, Doug EB, Nathan DG, Edward HK, Arnau C-M, Albert IK, Amyn AM, Dennis W, Mike W, Joshua LW, Daniel MW, Saad BO. 2020. SARS-CoV-2 RNA concentrations in primary municipal sewage sludge as a leading indicator of COVID-19 outbreak dynamics. medRxiv: 2020.2005.2019.20105999.

Kanwar VS, Sharma A, Rinku, Kanwar M, Srivastav AL, Soni DK. 2023. An overview for biomedical waste management during pandemic like COVID-19. International Journal of Environmental science and technology, 20(7): 8025–8040.

Kasloff SB, Leung A, Strong JE, Funk D, Cutts T. 2021. Stability of SARS-CoV-2 on critical personal protective equipment. Scientific reports, 11(1): 984.

Katoto PDMC, Brand AS, Bakan B, Obadia PM, Kuhangana C, Kayembe-Kitenge T, Kitenge JP, Nkulu CBL, Vanoirbeek J, Nawrot TS. 2021. Acute and chronic exposure to air pollution in relation with incidence, prevalence, severity and mortality of COVID-19: a rapid systematic review. Environmental health, 20: 1–21.

Khan Z, Ualiyeva D, Khan A, Zaman N, Sapkota S, Khan A, Ali B, Ghafoor D. 2021. A correlation among the COVID-19 spread, particulate matters, and angiotensin-converting enzyme 2: a review. Journal of environmental and public health, 2021: 1–8.

Kitajima M, Ahmed W, Bibby K, Carducci A, Gerba CP, Hamilton KA, Haramoto E, Rose JB. 2020. SARS-CoV-2 in wastewater: State of the knowledge and research needs. Science of the total environment, 739: 139076.

Klemeš JJ, Fan YV, Jiang P. 2020. The energy and environmental footprints of COVID-19 fighting measures – PPE, disinfection, supply chains. Energy, 211: 118701.

Kocamemi BA, Kurt H, Sait A, Sarac F, Saatci AM, Pakdemirli B. 2020. SARS-CoV-2 detection in Istanbul wastewater treatment plant sludges. medRxiv: 2020-2005.

Kumar M, Patel AK, Shah AV, Raval J, Rajpara N, Joshi M, Joshi CG. 2020. First proof of the capability of wastewater surveillance for COVID-19 in India through detection of genetic material of SARS-CoV-2. Science of the total environment, 746: 141326.

La Rosa G, Iaconelli M, Mancini P, Ferraro GB, Veneri C, Bonadonna L, Lucentini L, Suffredini E. 2020. First detection of SARS-CoV-2 in untreated wastewaters in Italy. Science of the total environment, 736: 139652.

Lackner M. 2000. Bioplastics. Kirk-Othmer Encyclopedia of chemical technology: 1–41.

Lai A, Chang ML, O'Donnell RP, Zhou C, Sumner JA, Hsiai TK. 2021. Association of COVID-19 transmission with high levels of ambient pollutants: Initiation and impact of the inflammatory response on cardiopulmonary disease. Science of the total environment, 779: 146464.

Li H, Xu XL, Dai DW, Huang ZY, Ma Z, Guan YJ. 2020. Air pollution and temperature are associated with increased COVID-19 incidence: a time series study. International journal of ınfectious diseases, 97: 278–282.

Liang Y, Tan Q, Song Q, Li J. 2021. An analysis of the plastic waste trade and management in Asia. Waste management, 119: 242–253.

Lim YK, Kweon OJ, Kim HR, Kim TH, Lee MK. 2021. The impact of environmental variables on the spread of COVID-19 in the Republic of Korea. Scientific reports, 11(1): 5977.

Lin S, Wei D, Sun Y, Chen K, Yang L, Liu B, Huang Q, Paoliello MMB, Li H, Wu S. 2020. Region-specific air pollutants and meteorological parameters influence COVID-19: A study from mainland China. Ecotoxicology and environmental Safety, 204: 111035.

Ling Y, Xu SB, Lin YX, Tian D, Zhu ZQ, Dai FH, Wu F, Song ZG, Huang W, Chen J. 2020. Persistence and clearance of viral RNA in 2019 novel coronavirus disease rehabilitation patients. Chinese medical journal, 133(09): 1039–1043.

Liu J, Zhou J, Yao J, Zhang X, Li L, Xu X, He X, Wang B, Fu S, Niu T. 2020. Impact of meteorological factors on the COVID-19 transmission: A multi-city study in China. Science of the total environment, 726: 138513.

Lodder W, de Roda Husman AM. 2020. SARS-CoV-2 in wastewater: potential health risk, but also data source. The lancet gastroenterology & hepatology, 5(6): 533–534.

Lundstrom K, Hromić-Jahjefendić A, Bilajac E, Aljabali AAA, Baralić K, Sabri NA, Shehata EM, Raslan M, Raslan SA, Ferreira ACBH. 2023. COVID-19 signalome: Potential therapeutic interventions. Cellular signalling, 103: 110559.

Maleki M, Anvari E, Hopke PK, Noorimotlagh Z, Mirzaee SA. 2021. An updated systematic review on the association between atmospheric particulate matter pollution and prevalence of SARS-CoV-2. Environmental research, 195: 110898.

Manoj MG, Satheesh Kumar MK, Valsaraj KT, Sivan C, Vijayan SK. 2020. Potential link between compromised air quality and transmission of the novel corona virus (SARS-CoV-2) in affected areas. Environmental research, 190: 110001.

Marquès M, Domingo JL. 2022. Positive association between outdoor air pollution and the incidence and severity of COVID-19. A review of the recent scientific evidences. Environmental research, 203: 111930.

Martinez GS, Linares C, De'Donato F, Diaz J. 2020. Protect the vulnerable from extreme heat during the COVID-19 pandemic. Environmental research, 187: 109684.

Medema G, Heijnen L, Elsinga G, Italiaander R, Brouwer A. 2020. Presence of SARS-Coronavirus-2 RNA in sewage and correlation with reported COVID-19 prevalence in the early stage of the epidemic in the Netherlands. Environmental science & technology letters, 7(7): 511–516.

Mendy A, Wu X, Keller JL, Fassler CS, Apewokin S, Mersha TB, Xie C, Pinney SM. 2021. Long-term exposure to fine particulate matter and hospitalization in COVID-19 patients. Respiratory medicine, 178: 106313.

Meo SA, Almutairi FJ, Abukhalaf AA, Alessa OM, Al-Khlaiwi T, Meo AS. 2021. Sandstorm and its effect on particulate matter PM2.5, carbon monoxide, nitrogen dioxide, ozone pollutants and SARS-CoV-2 cases and deaths. Science of the Total Environment, 795: 148764.

Morawska L, Johnson GR, Ristovski ZD, Hargreaves M, Mengersen K, Corbett S, Chao CYH, Li Y, Katoshevski D. 2009. Size distribution and sites of origin of droplets expelled from the human respiratory tract during expiratory activities. Journal of aerosol science, 40(3): 256–269.

Nemudryi A, Nemudraia A, Wiegand T, Surya K, Buyukyoruk M, Cicha C, Vanderwood KK, Wilkinson R, Wiedenheft B. 2020. Temporal detection and phylogenetic assessment of SARS-CoV-2 in municipal wastewater. Cell reports medicine, 1(6).

Núñez-Delgado A. 2020. SARS-CoV-2 in soils. Environmental research, 190: 110045.

Onakpoya IJ, Heneghan CJ, Spencer EA, Brassey J, Plüddemann A, Evans DH, Conly JM, Jefferson T. 2021. SARS-CoV-2 and the role of fomite transmission: a systematic review. F1000Research, 10.

Orive G, Lertxundi U, Barcelo D. 2020. Early SARS-CoV-2 outbreak detection by sewage-based epidemiology. Science of the total environment, 732: 139298.

Peccia J, Zulli A, Brackney DE, Grubaugh ND, Kaplan EH, Casanovas-Massana A, Ko AI, Malik AA, Wang D, Wang M. 2020. Measurement of SARS-CoV-2 RNA in wastewater tracks community infection dynamics. Nature biotechnology, 38(10): 1164–1167.

Piscitelli P, Miani A, Setti L, De Gennaro G, Rodo X, Artinano B, Vara E, Rancan L, Arias J, Passarini F. 2022a. The role of outdoor and indoor air quality in the spread of SARS-CoV-2: Overview and recommendations by the research group on COVID-19 and particulate matter (RESCOP commission). Environmental research, 211: 113038.

Piscitelli P, Miani A, Setti L, De Gennaro G, Rodo X, Artinano B, Vara E, Rancan L, Arias J, Passarini F, Barbieri P, Pallavicini A, Parente A, D'Oro EC, De Maio C, Saladino F, Borelli M, Colicino E, Gonçalves LMG, Di Tanna G, Colao A, Leonardi GS, Baccarelli A, Dominici F, Ioannidis JPA, Domingo JL. 2022b. The role of outdoor and indoor air quality in the spread of SARS-CoV-2: Overview and recommendations by the research group on COVID-19 and particulate matter (RESCOP commission). Environmental research, 211: 113038.

Polo D, Quintela-Baluja M, Corbishley A, Jones DL, Singer AC, Graham DW, Romalde JL. 2020. Making waves: Wastewater-based epidemiology for COVID-19–approaches and challenges for surveillance and prediction. Water research, 186: 116404.

Pourcher A-M, Françoise P-B, Virginie F, Agnieszka G, Vasilica S, Gérard M. 2007. Survival of faecal indicators and enteroviruses in soil after land-spreading of municipal sewage sludge. Applied soil ecology, 35(3): 473–479.

Pousada-Ferradás Y, Seoane-Labandeira S, Mora-Gutiérrez A, Núñez-Delgado A. 2012. Risk of water pollution due to ash–sludge mixtures: column trials. International Journal of environmental science and technology, 9: 21–29.

Pozzer A, Dominici F, Haines A, Witt C, Münzel T, Lelieveld J. 2020. Regional and global contributions of air pollution to risk of death from COVID-19. Cardiovascular research, 116(14): 2247–2253.

Ram K, Thakur RC, Singh DK, Kawamura K, Shimouchi A, Sekine Y, Nishimura H, Singh SK, Pavuluri CM, Singh RS. 2021. Why airborne transmission hasn't been conclusive in case of COVID-19? An atmospheric science perspective. Science of the Total Environment, 773: 145525.

Ramadan N, Shaib H. 2019. Middle East respiratory syndrome coronavirus (MERS-CoV): A review. Germs, 9(1): 35–42.

Ramirez Arenas L, Ramseier Gentile S, Zimmermann S, Stoll S. 2022. Fate and removal efficiency of polystyrene nanoplastics in a pilot drinking water treatment plant. Science of the total environment, 813: 152623.

Randazzo W, Cuevas-Ferrando E, Sanjuán R, Domingo-Calap P, Sánchez G. 2020a. Metropolitan wastewater analysis for COVID-19 epidemiological surveillance. International journal of hygiene and environmental health, 230: 113621.

Randazzo W, Truchado P, Cuevas-Ferrando E, Simón P, Allende A, Sánchez G. 2020b. SARS-CoV-2 RNA in wastewater anticipated COVID-19 occurrence in a low prevalence area. Water research, 181: 115942.

Rimoldi SG, Stefani F, Gigantiello A, Polesello S, Comandatore F, Mileto D, Maresca M, Longobardi C, Mancon A, Romeri F. 2020. Presence and infectivity of SARS-CoV-2 virus in wastewaters and rivers. Science of the total environment, 744: 140911.

Şahin M. 2020. Impact of weather on COVID-19 pandemic in Turkey. Science of the total environment, 728: 138810.

Sajadi MM, Habibzadeh P, Vintzileos A, Shokouhi S, Miralles-Wilhelm F, Amoroso A. 2020. Temperature, humidity, and latitude analysis to predict potential spread and seasonality for COVID-19. Social science research network.

Salmaan S, Aamer I, Adnan K, Muhammad S, Nayab M, Yasir A, Jamal A, Rana Muhammad S, Mehar A, Muhammad Masroor A, Lubna R, Ghulam M, Jaffar H, Johar A, Ribqa A, Muhammad Wasif M, Zeeshan Iqbal B, Muhammad Suleman R, Muhammad U, Muhammad Qaisar A, Abdul A, Nazish B, Massab U, Sana T, Asiya A, Faheem T, Nida A. 2020. Detection of SARS-CoV-2 in wastewater, using the existing environmental surveillance network: An epidemiological gateway to an early warning for COVID-19 in communities. medRxiv: 2020.2006.2003.20121426.

Sangkham S. 2020. Face mask and medical waste disposal during the novel COVID-19 pandemic in Asia. Case studies in chemical and environmental engineering, 2: 100052.

Sangkham S, Thongtip S, Vongruang P. 2021. Influence of air pollution and meteorological factors on the spread of COVID-19 in the Bangkok Metropolitan Region and air quality during the outbreak. Environmental research, 197: 111104.

Senatore V, Zarra T, Buonerba A, Choo K-H, Hasan SW, Korshin G, Li C-W, Ksibi M, Belgiorno V, Naddeo V. 2021. Indoor versus outdoor transmission of SARS-COV-2: environmental factors in virus spread and underestimated sources of risk. Euro-Mediterranean Journal for environmental ıntegration, 6: 1–9.

Serra-Compte A, González S, Arnaldos M, Berlendis S, Courtois S, Loret JF, Schlosser O, Yáñez AM, Soria-Soria E, Fittipaldi M, Saucedo G, Pinar-Méndez A, Paraira M, Galofré B, Lema JM, Balboa S, Mauricio-Iglesias M, Bosch A, Pintó RM, Bertrand I, Gantzer C, Montero C, Litrico X. 2021. Elimination of SARS-CoV-2 along wastewater and sludge treatment processes. Water research, 202: 117435.

Setti L, Passarini F, De Gennaro G, Barbieri P, Perrone MG, Borelli M, Palmisani J, Di Gilio A, Torboli V, Fontana F, Clemente L, Pallavicini A, Ruscio M, Piscitelli P, Miani A. 2020. SARS-CoV-2 RNA found on particulate matter of Bergamo in Northern Italy: First evidence. Environmental research, 188: 109754.

Shahzad F, Shahzad U, Fareed Z, Iqbal N, Hashmi SH, Ahmad F. 2020. Asymmetric nexus between temperature and COVID-19 in the top ten affected provinces of China: a current application of quantile-on-quantile approach. Science of the total environment, 736: 139115.

Shao L, Ge S, Jones T, Santosh M, Silva LFO, Cao Y, Oliveira MLS, Zhang M, BéruBé K. 2021. The role of airborne particles and environmental considerations in the transmission of SARS-CoV-2. Geoscience frontiers, 12(5): 101189.

Sherchan SP, Shahin S, Ward LM, Tandukar S, Aw TG, Schmitz B, Ahmed W, Kitajima M. 2020. First detection of SARS-CoV-2 RNA in wastewater in North America: a study in Louisiana, USA. Science of the total environment, 743: 140621.

Shi P, Dong Y, Yan H, Li X, Zhao C, Liu W, He M, Tang S, Xi S. 2020. The impact of temperature and absolute humidity on the coronavirus disease 2019 (COVID-19) outbreak—evidence from China. medRxiv: 2020-2003.

Shrestha LB, Foster C, Rawlinson W, Tedla N, Bull RA. 2022. Evolution of the SARS-CoV-2 omicron variants BA.1 to BA.5: implications for immune escape and transmission. Reviews in medical virology, 32(5): e2381.

Sobral MFF, Duarte GB, da Penha Sobral AIG, Marinho MLM, de Souza Melo A. 2020. Association between climate variables and global transmission of SARS-CoV-2. Science of the total environment, 729: 138997.

Srivastava A. 2021. COVID-19 and air pollution and meteorology—an intricate relationship: A review. Chemosphere, 263: 128297.

Sudipti A, Aditi N, Jasmine S, Jayana R, Sonika S, Sandeep KS, Gupta AB. 2020. Sewage surveillance for the presence of SARS-CoV-2 genome as a useful wastewater based epidemiology (WBE) tracking tool in India. medRxiv: 2020.2006.2018.20135277.

Tang A, Tong ZD, Wang HL, Dai YX, Li KF, Liu JN, Wu WJ, Yuan C, Yu ML, Li P. 2020a. Detection of novel coronavirus by RT-PCR in stool specimen from asymptomatic child, China. Emerging ınfectious diseases, 26: 584.

Tang AN, Tong Z-d, Wang H-l, Dai Y-x, Li K-f, Liu J-n, Wu W-j, Yuan C, Yu M-l, Li P. 2020b. Detection of novel coronavirus by RT-PCR in stool specimen from asymptomatic child, China. emerging ınfectious diseases, 26(6): 1337.

Teymourian T, Teymoorian T, Kowsari E, Ramakrishna S. 2021. Challenges, strategies, and recommendations for the huge surge in plastic and medical waste during the global COVID-19 pandemic with circular economy approach. Materials circular economy, 3: 1-14.

Thompson RC, Moore CJ, Vom Saal FS, Swan SH. 2009. Plastics, the environment and human health: current consensus and future trends. Philosophical transactions of the royal society b: biological sciences, 364(1526): 2153-2166.

Tian Y, Rong L, Nian W, He Y. 2020. Review article: gastrointestinal features in COVID-19 and the possibility of faecal transmission. Alimentary pharmacology & therapeutics, 51: 843-851.

Tosepu R, Gunawan J, Effendy DS, Lestari H, Bahar H, Asfian P. 2020. Correlation between weather and COVID-19 pandemic in Jakarta, Indonesia. Science of the total environment, 725: 138436.

Tran HN, Le GT, Nguyen DT, Juang R-S, Rinklebe J, Bhatnagar A, Lima EC, Iqbal HMN, Sarmah AK, Chao H-P. 2021. SARS-CoV-2 coronavirus in water and wastewater: A critical review about presence and concern. Environmental research, 193: 110265.

Van Doremalen N, Bushmaker T, Morris DH, Holbrook MG, Gamble A, Williamson BN, Tamin A, Harcourt JL, Thornburg NJ, Gerber SI, Lloyd-Smith JO, de Wit E, Munster, V. J. (2020). Aerosol and surface stability of SARS-CoV-2 as compared with SARS-CoV-1. New England journal of medicine, *382*(16), 1564-1567.

Vanapalli KR, Sharma HB, Ranjan VP, Samal B, Bhattacharya J, Dubey BK, Goel S. 2021. Challenges and strategies for effective plastic waste management during and post COVID-19 pandemic. Science of the total environment, 750: 141514.

Wang B, Chen H, Chan YL, Oliver BG. 2020a. Is there an association between the level of ambient air pollution and COVID-19? American Journal of physiology-lung cellular and molecular physiology, 319(3): L416-L421.

Wang J, Feng H, Zhang S, Ni Z, Ni L, Chen Y, Zhuo L, Zhong Z, Qu T. 2020b. SARS-CoV-2 RNA detection of hospital isolation wards hygiene monitoring during the Coronavirus Disease 2019 outbreak in a Chinese hospital. International journal of ınfectious diseases, 94: 103-106.

Wang W, Xu Y, Gao R, Lu R, Han K, Wu G, Tan W. 2020c. Detection of SARS-CoV-2 in Different Types of Clinical Specimens. The journal of the american medical association, 323(18): 1843-1844.

Weidhaas J, Aanderud ZT, Roper DK, VanDerslice J, Gaddis EB, Ostermiller J, Hoffman K, Jamal R, Heck P, Zhang Y. 2021. Correlation of SARS-CoV-2 RNA in wastewater with COVID-19 disease burden in sewersheds. Science of the total environment, 775: 145790.

Westhaus S, Weber F-A, Schiwy S, Linnemann V, Brinkmann M, Widera M, Greve C, Janke A, Hollert H, Wintgens T. 2021. Detection of SARS-CoV-2 in raw and treated wastewater in Germany–suitability for COVID-19 surveillance and potential transmission risks. Science of the Total environment, 751: 141750.

Williams-Wynn MD, Naidoo P. 2020. A review of the treatment options for marine plastic waste in South Africa. Marine pollution bulletin, 161: 111785.

Wölfel R, Corman VM, Guggemos W, Seilmaier M, Zange S, Müller MA, Niemeyer D, Jones TC, Vollmar P, Rothe C. 2020. Virological assessment of hospitalized patients with COVID-2019. Nature, 581(7809): 465-469.

Woodby B, Arnold MM, Valacchi G. 2021. SARS-CoV-2 infection, COVID-19 pathogenesis, and exposure to air pollution: What is the connection? Annals of the new york academy of sciences, 1486(1): 15-38.

Wu F, Zhang J, Xiao A, Gu X, Lee WL, Armas F, Kauffman K, Hanage W, Matus M, Ghaeli N, Endo N, Duvallet C, Poyet M, Moniz K, Washburne AD, Erickson TB, Chai PR, Thompson J, Alm EJ. 2020a. SARS-CoV-2 Titers in Wastewater Are Higher than Expected from Clinically Confirmed Cases. mSystems, 5(4): e00614-20.

Wu F, Zhang J, Xiao A, Gu X, Lee WL, Armas F, Kauffman K, Hanage W, Matus M, Ghaeli N, Endo N, Duvallet C, Poyet M, Moniz K, Washburne AD, Erickson TB, Chai PR, Thompson J, Alm EJ. 2020b. SARS-CoV-2 Titers in wastewater are higher than expected from clinically confirmed cases. mSystems, 5(4): e00614-20.

Wu X, Braun D, Schwartz J, Kioumourtzoglou MA, Dominici F. 2020d. Evaluating the impact of long-term exposure to fine particulate matter on mortality among the elderly. Science advances, 6(29): eaba5692.

Wu Y, Guo C, Tang L, Hong Z, Zhou J, Dong X, Yin H, Xiao Q, Tang Y, Qu X. 2020e. Prolonged presence of SARS-CoV-2 viral RNA in faecal samples. The lancet gastroenterology & hepatology, 5(5): 434-435.

Wurtzer S, Marechal V, Mouchel J, Maday Y, Teyssou R, Richard E, Almayrac J, Moulin L. 2020a. Evaluation of lockdown impact on SARS-CoV-2 dynamics through viral genome quantification in Paris wastewaters. medRxiv, 2020.04.12.20062679.

Wurtzer S, Marechal V, Mouchel JM, Maday Y, Teyssou R, Richard E, Almayrac JL, Moulin EL. 2020b. Evaluation of lockdown effect on SARS-CoV-2 dynamics through viral genome quantification in wastewater, Greater Paris, France, 5 March to 23 April 2020. Eurosurveillance, 25(50): 2000776.

Yang Z, Li G, Dai X, Liu G, Li G, Jie Y. 2020. Three cases of novel coronavirus pneumonia with viral nucleic acids still positive in stool after throat swab detection turned negative. Chinese journal of digestion, E002-E002.

Zhang J, Wang S, Xue Y. 2020a. Fecal specimen diagnosis 2019 novel coronavirus-infected pneumonia. Journal of medical virology, 92(6): 680-682.

Zhang N, Gong Y, Meng F, Shi Y, Wang J, Mao P, Chuai X, Bi Y, Yang P, Wang F. 2021. Comparative study on virus shedding patterns in nasopharyngeal and fecal specimens of COVID-19 patients. Science china life sciences, 64(3): 486-488.

Zhang Y, Chen C, Zhu S, Shu C, Wang D, Song J, Song Y, Zhen W, Feng Z, Wu G. 2020b. Isolation of 2019-nCoV from a stool specimen of a laboratory-confirmed case of the coronavirus disease 2019 (COVID-19). China CDC weekly, 2(8): 123-124.

Zhao C, Fang X, Feng Y, Fang X, He J, Pan H. 2021. Emerging role of air pollution and meteorological parameters in COVID-19. Journal of evidence-based medicine, 14(2): 123-138.

Zhu C, Maharajan K, Liu K, Zhang Y. 2021. Role of atmospheric particulate matter exposure in COVID-19 and other health risks in human: A review. Environmental research, 198: 111281.

Zoran MA, Savastru RS, Savastru DM, Tautan MN. 2020. Assessing the relationship between ground levels of ozone (O3) and nitrogen dioxide (NO2) with coronavirus (COVID-19) in Milan, Italy. Science of the total environment, 740: 140005.