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Focus paper

The role of airborne particles and environmental considerations in the transmission of SARS-CoV-2

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ABSTRACT

Corona Virus Disease 2019 (COVID-19) caused by the novel coronavirus, results in an acute respiratory condition coronavirus 2 (SARS-CoV-2) and is highly infectious. The recent spread of this virus has caused a global pandemic. Currently, the transmission routes of SARS-CoV-2 are being established, especially the role of environmental transmission. Here we review the environmental transmission routes and persistence of SARS-CoV-2. Recent studies have established that the transmission of this virus may occur, amongst others, in the air, water, soil, cold-chain, biota, and surface contact. It has also been found that the survival potential of the SARS-CoV-2 virus is dependent on different environmental conditions and pollution. Potentially important pathways include aerosol and fecal matter. Particulate matter may also be a carrier for SARS-CoV-2. Since microscopic particles can be easily absorbed by humans, more attention must be focused on the dissemination of these particles. These considerations are required to evolve a theoretical platform for epidemic control and to minimize the global threat from future epidemics.

Contents

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1. Introduction

In December 2019, an outbreak of pneumonia of unknown etiology emerged in the city of Wuhan China, from which the novel coronavirus strain was isolated (2019-nCoV/ SARS-CoV-2) (Li et al., 2020b). The virus is generally referred to as 'novel Coronavirus'. On February 11th, 2020, the World Health Organization (WHO) announced that the disease was caused by the virus named Corona Virus Disease 2019 (COVID-19). It has infected more than 100 million individuals and resulted in more than 2 million deaths as of 14 March 2021 (WHO, 2021). Reddy et al. (2021) used previously validated phenomenological models and several non-linear growth curves to predict cases and deaths of COVID-19. Debate continues about how SARS-CoV-2 is spread in the air. However, growing evidence has highlighted that infective micro-droplets are small enough to remain suspended in the air (Anderson et al., 2020; Kohanski et al., 2020). The airborne transmission of aerosolized viruses will contribute towards the widespread distribution of COVID-19 in such a short time (Froum and Froum, 2020; Khan and Parab, 2020). Research has shown that the virus could be electrostatically attracted to charged nanofibers in filtration systems, with the potential of the virus attaching to free, potentially respirable, airborne fibers or particles in the atmosphere (Leung and Sun, 2020). This has led researchers to investigate the role of microscopic particles in the spread of SARS-CoV-2.

The British government announced the discovery of the new variant of the SARS-CoV-2 in mid-December 2020; evidence shows this new variant of SARS-CoV-2 transmits more easily than other strains (UK Government, 2020). In Brazil and South Africa, new mutations of viruses have also been reported (Koyama et al., 2020; Tegally et al., 2020; Sabino et al., 2021; Tang et al., 2021). The WHO stated that mutated SARS-CoV-2 will present new challenges. Because of the high infectivity and mutability of COVID-19, the environmental transmission routes of SARS-CoV-2 are a subject of urgent research. Some studies identify the main routes of transmission as respiratory droplets (Azuma et al., 2020; Marin-Garcia et al., 2021) and close contact (Martinez-Fierro et al., 2021). People may also become infected through physical contact of virus-contaminated objects such as solid waste (Al Huraimel et al., 2020; Ben-Shmuel et al., 2020; Suman et al., 2020). Aerosol transmission in a relatively closed environment (Azuma et al., 2020; Zhao et al., 2020; Tung et al., 2021), such as hospital locals have been confirmed (Shi et al., 2020). In addition, environmental pollution caused by feces and urine aerosols (Heller et al., 2020) or physical contact in toilets (Hoseinzadeh et al., 2020; Mehraeen et al., 2020; Pamplona et al., 2020) could pose a major transmission risk. This illustrates the importance of environmental factors in transmission routes. In previous studies, the exhaled droplet transmission and close contact (e.g., contaminated hands and surfaces) were considered the main mode of transmission (Li et al., 2020a; Wong et al., 2020b), and maintaining a social distance of two meters or more between people was stipulated to minimize the risk of transmission (Bian et al., 2020; Schroter, 2020). The available studies underpin the importance of environmental factors in transmission routes of COVID-19. In this review, we consider possible transmission routes of COVID-19 and different mutations of the virus via environmental media. The survival ability of SARS-CoV-2 in relation to the different environmental conditions is also discussed.

2. The biology of SARS-CoV-2

SARS-CoV-2 is a Betacoronavirus that is coated with a rigid envelope of protein to resist the antimicrobial enzymes in body fluids and lower inner shell disorder (Goh et al., 2020). Electron micrographs of SARS-CoV-2 (CDC, 2020) reveal a diverging spherical outline with some degree of pleomorphism, with virion diameters varying from 60 to 140 nm (Zhu et al., 2020b) (Fig. 1). CDC (2020) also reveals ultrastructural morphology exhibited by coronaviruses (Fig. 2). Specifically, the spikes that adorn the outer surface of the virus, which impart the look of a corona surrounding the virion, when viewed under electron microscopy (CDC, 2020). SARS-CoV-2 is constituted of structural proteins, including spike (S) glycoproteins, membrane (M) glycoproteins, envelope, and nucleocapsid (N) proteins. S glycoprotein binds to cell surface receptor angiotensin-converting enzyme II (ACE2) through receptor binding domain (RBD) (Yao et al., 2020). The initial symptoms of COVID-19 include respiratory symptoms, fever, cough, loss of taste and smell, and dyspnea. More severe infections can lead to pneumonia, severe acute respiratory syndrome, renal failure, and death (Huang et al., 2020a). A significant proportion of the patients also developed gastrointestinal symptoms such as abdominal pain, vomiting, nausea, anorexia, and diarrhea (Chen et al., 2020a).

Many studies have reported similarities between SARS-CoV-2 and other coronaviruses such as severe acute respiratory syndrome coronavirus-1, SARS-CoV-1; a bat coronavirus, and BatCoV RaTG13. In terms of nucleotide sequences, the homology of SARS-CoV-2 was 79% with SARS-CoV-1 and 96% with BatCoV RaTG13. This is markedly similar to BatCoV RaTG13. SARS-CoV-2 and SARS-CoV-1 are similar in that they both use angiotensin-converting enzyme II (ACE2) as the receptor of the virus (Zhou et al., 2020). The coronavirus binds to ACE2 receptors and enters the cells, causing infection and disease (Lu et al., 2020b; Tung et al., 2021). Studies on infectivity in cells show that SARS-CoV-2 may have a higher binding affinity to ACE2 than SARS-CoV-1 (Chen et al., 2020c), and this suggests that SARS-CoV-2 may infect human lung cells more effectively. SARS-CoV-2 and SARS-CoV-1 have similar receptor binding domains but SARS-CoV-2 and BatCoV RaTG13 receptor binding domains have low similarity, indicating that there is an intermediate host between bats and humans (Wong et al., 2020a). In terms of mortality, SARS-CoV-2 is less deadly but far more transmissible than SARS-CoV-1 (Koma et al., 2020; Petersen et al., 2020). The mortalities caused by COVID-19 vary between countries. Persons of color (POC, highest-risk phenotypes) developing COVID-19

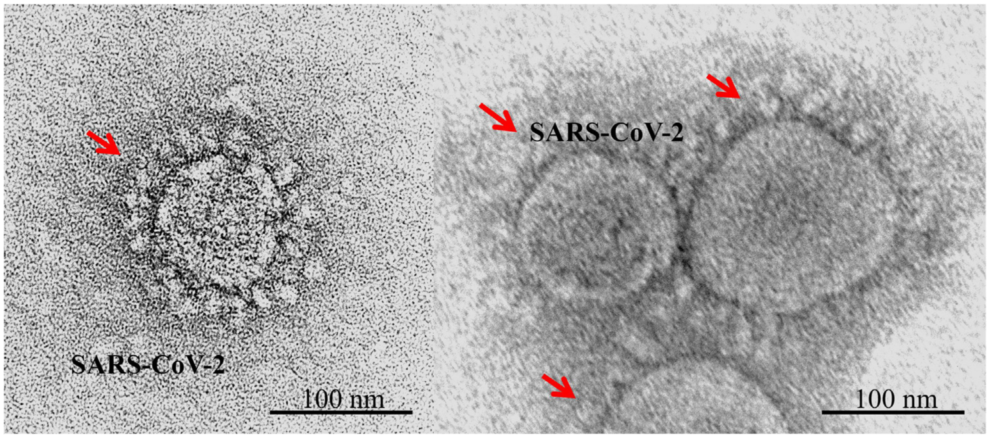

Fig. 1. Morphological characteristics of SARS-CoV-2 as viewed by transmission electron microscopy. The spherical viral particles may range from 60 to 140 nm in diameter (CDC, 2020).

infection are more likely to die disproportionately (Asare et al., 2020). The co-morbidities of diabetes, hypertension, cardiovascular disease, and the higher prevalence of obesity have provided hosts for viruses like COVID-19 to thrive and cause serious infections (Asare et al., 2020; Caci et al., 2020; Gasparotto et al., 2019; Giorgino et al., 2020). There is awareness of elderly people and those with immunocompromised conditions being more vulnerable to catching COVID-19 (Schmidt et al., 2020).

3. Overview of possible transmission pathways

There is a plethora of studies that indicate the novel coronavirus transmission to be strongly influenced by environmental factors. The currently accepted pathways are respiratory droplets and close contact, touching virus-contaminated objects (Ben-Shmuel et al., 2020), aerosol transmission in closed environments (Shi et al., 2020), feces and urine aerosol, or contact in toilets (Pamplona et al., 2020), and cold-chain transmission (Han et al., 2020b; Liu et al., 2020b). In general, SARS-CoV-2 has been found in the environment, including air, water, soil, biota, surfaces, and cold-chain (Fig. 3, Table 1). Some of these pathways overlap, resulting in potentially complex transmission pathways.

3.1. Airborne transmission of SARS-CoV-2

3.1.1. Modes of airborne transmission

The virus may be enveloped in the interior or adhere to the surface of respiratory droplets and aerosols. In the ambient air, the liquid droplets can encrust and absorb finer aerosol particles (Freney et al., 2010; Yuan et al., 2019). Fig. 4 showed some typical images of ambient aerosol particles including biogenic particle, fly ash, mineral, soot, and liquid droplets. According to their aerodynamic diameter, the ambient aerosol particles are divided into PM_{10} (particulate matter less than 10 μm), $PM_{2.5}$ (particulate matter less than 2.5 μm), and nanoparticles (Shao et al., 2018; Boongla et al., 2020; Chen et al., 2020b). Nano-aerosol particles are airborne aerosols up to 100 nm (Leung et al., 2018) (Fig. 4). The respiratory aerosols are classified into droplets and aerosol, with the main differences between respiratory aerosols and droplets and various ambient aerosol particles being the particle sizes (Fig. 5). The WHO defined the respiratory particles larger than 5 μm as droplets and those smaller than 5 μm as respiratory aerosols (WHO, 2014). However, the respiratory aerosol is different from an ambient aerosol defined in atmospheric science where it generally refers to the suspension system of solid particles, liquid particles, or both of them in a gaseous medium (Tang et al., 2006; Freney et al., 2010). Ambient aerosol is considered potentially harmful to human health as it can contain not only hazardous elements and chemicals (Shao et al., 2017; Feng et al., 2020; Rao et al., 2020), but also pathogens such as bacteria, fungi, and viruses (Han et al., 2021). Airborne fine particles ($PM_{2.5}$) are considered of greater health significance with their large surface area and strong adsorption capability (Ding and Zhu, 2003; Shao et al., 2018). Respiratory droplets are produced by any action resulting in the energetic release of air from the mouth or nose, such as coughing, sneezing, talking, and singing (emission jets) (Xie et al., 2009). The potential transmission of SARS-CoV-2 in the air is mainly from respiratory droplets and aerosols (Azuma et al., 2020; Jayaweera et al., 2020). Studies have indicated that aerosols containing SARS-CoV-2 are mainly distributed in two size ranges that include 0.25–1.0 μm and > 2.5 μm, respectively (Liu et al., 2020a).

It is generally accepted that the larger respiratory particles travel shorter distances, dropping out of the air sooner, and potentially increasing the risk of contamination on proximal surfaces. Epidemiological and pathogen infection experiments conclude that the range of respiratory droplet infection is typically within 1 m away from the source of infection (WHO, 2014). In contrast, respiratory aerosols may be suspended in the air for long periods of time due to Brownian motion, and thus, travel over greater distances; therefore, aerosol propagation is possible (Jayaweera

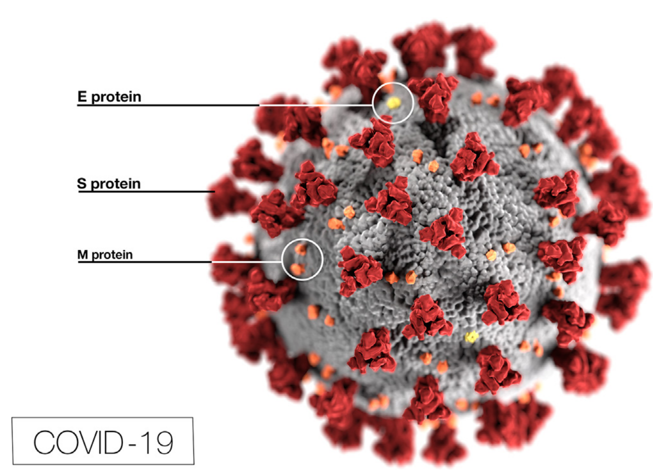

Fig. 2. Molecular architecture of SARS-CoV-2 which contains structural proteins (CDC, 2020).

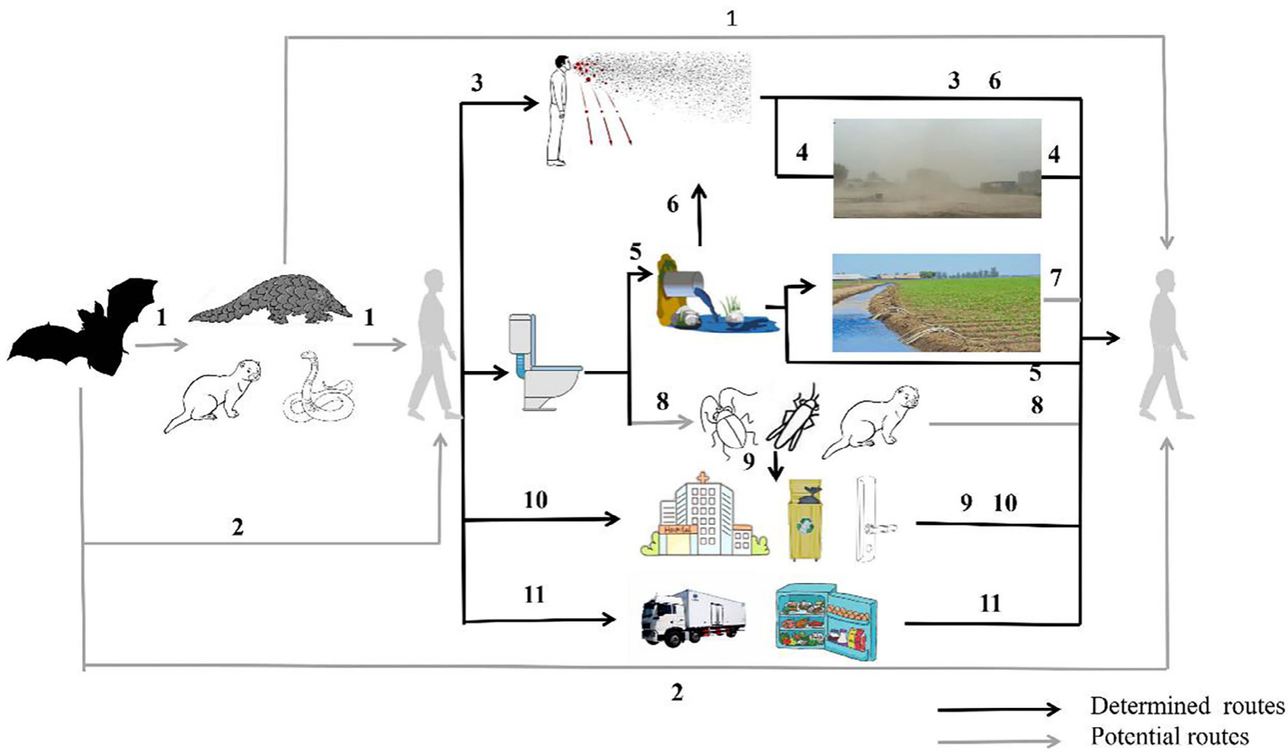

Fig. 3. A schematic diagram to show the different environmental transmission routes of SARS-CoV-2 in animals and humans. Routes 1 and 2: Bats may either directly or indirectly act as a vector to pass on the SARS-CoV-2 viral infection to humans; Route 3: Infections are caused directly or indirectly by aerosols and droplets exhaled by the humans; Route 4: Falling aerosols or droplets may resuspend through the soil causing transmission; Route 5: The entry of excreta into sewage may cause water spread; Route 6: The excreta enters the sewage and the virus-containing air around the sewage may cause transmission; Route 7: Water containing the virus entering the soil can cause infection; Route 8: Animals (e.g., cockroaches) that can transmit pathogens to humans may cause the spread of SARS-CoV-2; Route 9: Animals can spread SARS-CoV-2 through contact with contaminated surfaces and secretions from sick people; Route 10: People can become infected by touching contaminated objects with their hands; Route 11: It may cause long-distance cold chain transmission through low temperature treatment of food, freezing storage and the cold-chain for transporting.

et al., 2020). However, this capacity of respiratory droplet and aerosol transmission can be influenced by environmental parameters (e.g., evaporation, humidity, gravity, wind speed, and wind direction). Respiratory droplet transmission induces mucocutaneous and respiratory tract infections, which has been of great concern to medical practitioners, whereas aerosol can transmit deeply into the respiratory tract including the alveolar region (Drossinos and Stilianakis, 2020). Microscopic particles can contain virus that can be absorbed to cause infection by (1) oral ingestion of contaminated food and water; (2) inhalation through the airway; and (3) dermal absorption (Bakshi, 2020; Leung and Sun, 2020; Silva et al., 2021; Romer et al., 2011). Virus-containing aerosol is most likely to penetrate deep into the distal respiratory airways of the lung. From there, they can penetrate the alveolar membrane, enter the bloodstream directly and translocate to vital organs (Drossinos and Stilianakis, 2020; Silva et al., 2020, 2021). Substances attached to smaller particles may have more harmful health effects than those attached to larger particles (Leung et al., 2018). Therefore, droplet and aerosol, especially finer aerosol, transmission cannot be ignored.

3.1.2. Examples of aerosols containing SARS-CoV-2

Evidence for the quantification and assessment of SARS-CoV-2 around the disease concentration areas is lacking, although there is evidence for the detection of virus-containing aerosols (Cao et al., 2021; Liu et al., 2020a). At present, there is no direct evidence that SARS-CoV-2 can be transmitted through the air. There are indications of viral-containing aerosols in many places. This may confirm that such a transmission pathway may be possible.

In hospital environments, the supportive therapy may produce aerosols containing viruses. The associated medical operations in relation to the virus transmission include bronchoscopy, cardiopulmonary resuscitation (CPR), non-invasive positive pressure ventilation (NPPV), tracheal intubation and extubation, tracheostomy, surgery, the suction of body fluids, nebulizer treatment, otolaryn-

Table 1
Transmission codes of SARS-CoV-2 in different environments.

Types of virus transmission	Virus transmission mode
Airborne transmission	The potential transmission of SARS-CoV-2 in the air is mainly from respiratory droplets and aerosols by coughing, sneezing, talking, and singing
Water transmission	Water transmission refers to bacteria and viruses discharged from the body through excreta to pollute the environment, followed by entry into the human respiratory and/or GIT to infect patients
Soil transmission	For one thing, contaminated soils are resuspended and inhaled by humans and animals. For another, water containing virus is discharged into soil or sludge may cause indirect diffusion of the soil near the water flow
Surface transmission	Infection may occur when humans make contact with the surface of contaminated objects and then the mucosal parts. Cold-chain transmission is a special surface propagation mode by frozen food's packaging materials
Biota transmission	On the one hand, some insects transmit the virus by contacting contaminated surfaces and secretions of patients. On the other hand, it is necessary to study whether animals (e.g., minks) infected with virus can be transmitted to humans

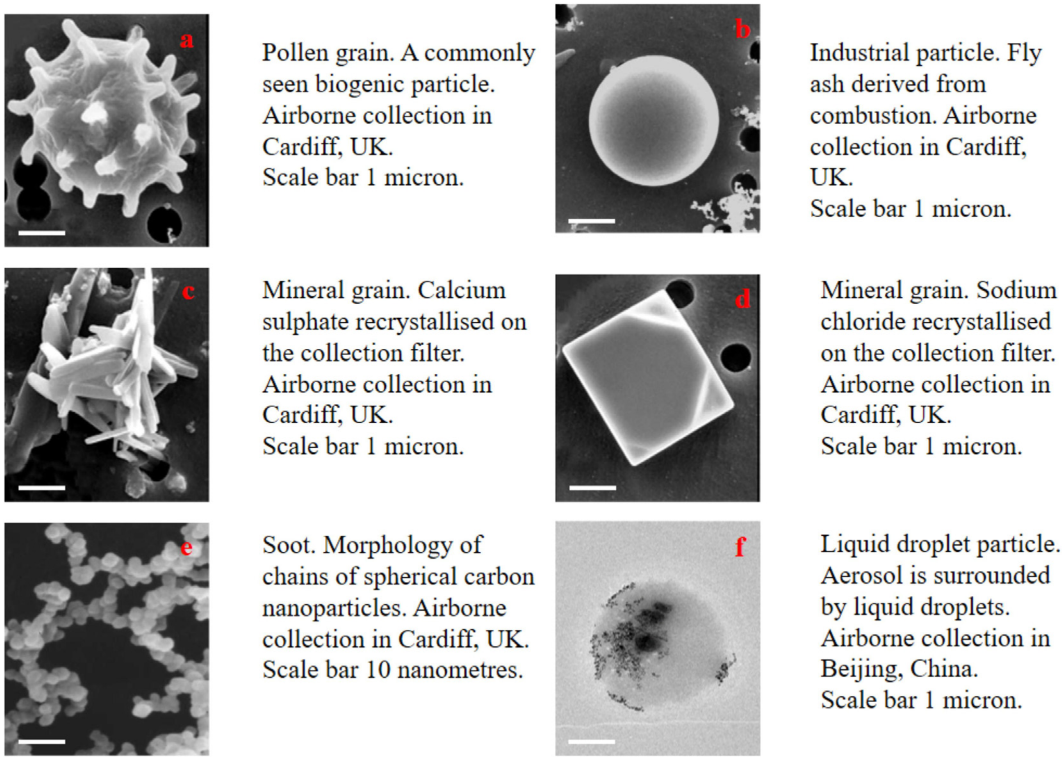

Fig. 4. Morphology and composition of different types of particles. (a–e) Scanning electron microscope [SEM] image. (f) Transmission electron microscope [TEM] image.

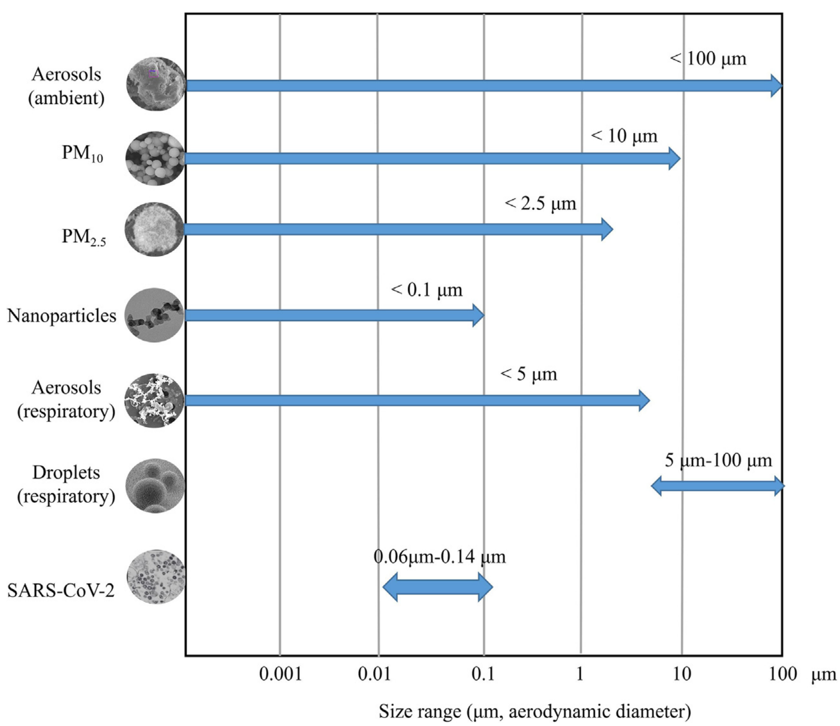

Fig. 5. The size range of different types of particles. The graph denotes the size ranges between ambient aerosol (e.g., Ca aluminium silicate Grossular) with irregular morphology; scanning electron microscope [SEM] image), PM_{10} (e.g., coal fly ash particles; SEM), $PM_{2.5}$ (e.g., an aggregate of carbon black particles, SEM image), nanoparticles (ultrafine particles) (e.g., aggregate, transmission electron microscope [TEM] image), respiratory aerosol (e.g. soot particles, SEM), respiratory droplets (SEM), virus SARS-CoV-2 (TEM). The SARS-CoV-2 viral particles with aerodynamic diameters of 0.06–0.14 μm fall within the "highly respirable" size range.

gology medical, and dental treatment (Table 2). The SARS-CoV-2 in dentistry and otolaryngology is found to be associated with the aerosol produced by mechanical oral transmission or coughing (Becker et al., 2020; Ralli et al., 2020). The airway operation (non-invasive positive, tracheal intubation and extubation, tracheostomy) during surgery will also produce the aerosols containing SARS-CoV-2 (Loth et al., 2020; Dhillon et al., 2021). The aerosols may also be produced when the anesthesiologist assists with airway management (e.g., mask ventilation, chest cavity) and CPR (Wong et al., 2020c). Health care workers performing bronchoscopy in emergency situations are at risk of aerosol transmission (Yamamoto et al., 2021). The non-invasive positive pressure ventilation (NPPV) patients infected with SARS-CoV-2 are at a high risk of transmitting the virus (Fujita and Suzuki, 2020). Aerosols containing SARS-CoV-2 RNA were detected in a hospital in Wuhan, China, and the viral load in ambient aerosols in the patient toilets was found to be highest, followed by the waiting-room for patient visitors (Liu et al., 2020a). Aerosol in these environments is usually produced by cough, surgery, mechanical transmission, and medical interventions that may cause infection of relevant supporting medical staff.

Indoor transmission of aerosols containing coronaviruses has been reported in a variety of cases. The case of the SARS-CoV-1 infection in Amoy Gardens, Hong Kong, in 2003, where a total of 321 people were infected, serves as a possible example of aerosol transmission of virus (Peiris et al., 2003; Lau et al., 2004). The aerosols exhaled by the residents were deposited on the indoor surface or in the suspended air. Firstly, virus-containing aerosols in the air were transmitted vertically through exhaust pipes (e.g., toilet and shower; Fig. 6). Secondly, when the residents discharged their waste (feces and urine) after using toilets, airflow was generated upon flushing the toilet and produced viral-containing aerosol transmission through the sewage pipe (Fig. 6) (Gormley et al., 2017). This in turn, increased the risk of infection, as novel coronavirus has been isolated from the feces of COVID-19 patients (Jones et al., 2020). Therefore, it is important to implement effective measures to prevent aerosol transmission caused by using "sitting" style toilets, such as increasing the toilet room ventilation and disinfection routines. Toilet and bathroom ventilation systems are also a potential route for airborne transmission, which draw air into the apartment and expedites long-distance transmission. Although there is no evidence that the virus can spread through air conditioning systems, it has been observed in some cases of "cluster outbreaks" that the airflow of air conditioning in a closed

Table 2
Medical operation and induction mechanism of aerosol generation in hospital.

Medical operation	Mechanism	References
Bronchoscopy	Cough	Yamamoto et al., 2021
Cardiopulmonary resuscitation (CPR)	Cough	Wong et al., 2020c
Non-invasive positive pressure ventilation (NPPV)	Mechanical transmission	Fujita and Suzuki, 2020
Tracheal intubation and extubation	Mechanical transmission	Dhillon et al., 2021
Tracheostomy	Mechanical transmission	Loth et al., 2020
Surgery	Surgery operation and mechanical transmission	Ralli et al., 2020
The suction of body fluids	Cough	Tran et al., 2012
Nebulizer treatment	Mechanical transmission	Tran et al., 2012
Otolaryngology medical	Mechanical transmission	Ralli et al., 2020
Dental treatment	Cough	Becker et al., 2020

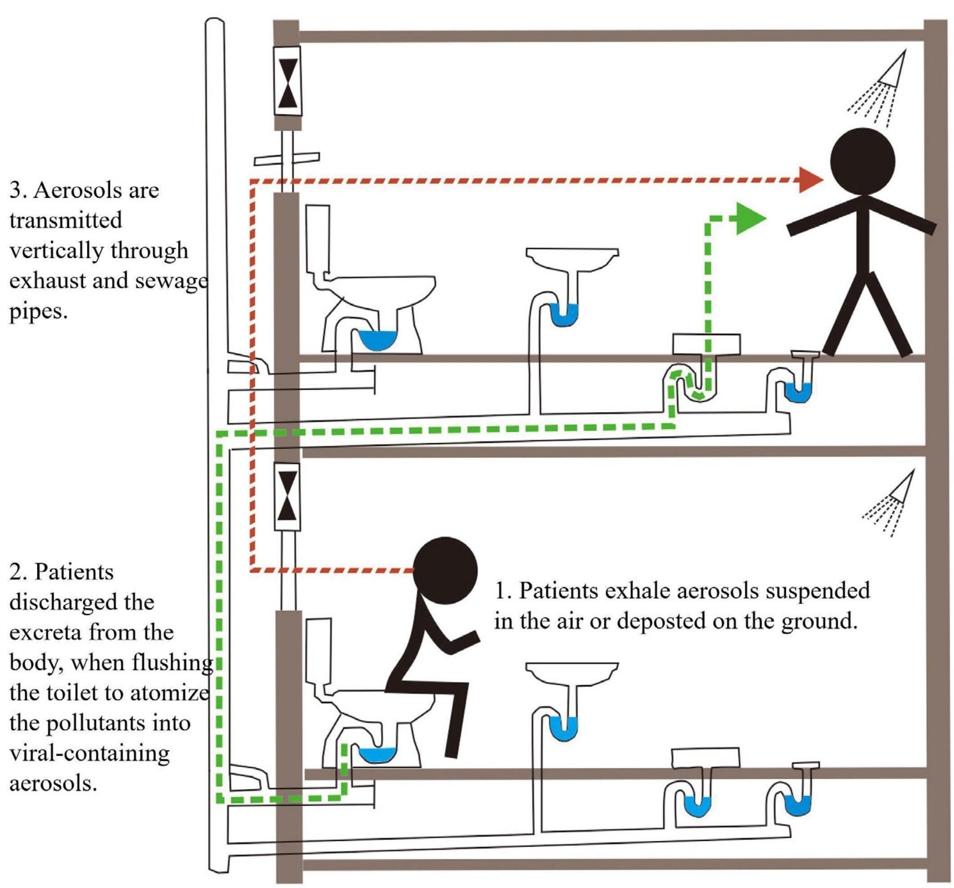

Fig. 6. Aerosol propagation in sewage pipes (modified after Gormley et al., 2017).

environment will affect the transmission of novel coronavirus (Lacatusu et al., 2020). Three families in a restaurant in Guangzhou who were seated according to the Worldwide social distance rule of "2 m separation between persons" developed COVID-19 symptoms (Lu et al., 2020a). The strong airflow atomization of air conditioning may have carried virus particles and caused transmission (Chirico et al., 2020). These case studies indicate that human generated aerosols containing novel coronavirus may exist in a relatively closed interior space for extended periods of time. Therefore, it is speculated that the aerosols and droplets produced by human respiratory performance may lead to the rapid spread of disease. Thus, further studies on the indoor transmission characteristics of aerosols containing the SARS-CoV-2 are required.

The outdoor transmission of SARS-CoV-2 is another possible route of the airborne transmission of virus. The highest concentration of a positive sample of novel coronavirus was detected in ventilation grills at a hospital in the United States treating patients with SARS-CoV-2 (Santarpia et al., 2020). This increases the likelihood that aerosols can travel outdoors. A study also suggests that conditions of greater atmospheric stability and dryness are conducive to the spread of SARS-CoV-2 (Sanchez-Lorenzo et al., 2020). A retrospective cohort study in the United States showed that incidence of COVID-19 cases was significantly higher in 14 out of 20 counties that had a large outdoor gathering 15 days prior (Miron et al., 2020). Therefore, it is important to note that infections are possible outdoors, and protective measures should be strengthened in outdoors.

In offices and outdoor environments, the number of nanoparticles is as high as 60–300 million count/m^3 (Leung et al., 2018). However, due to the difficulty of observation and sampling, there is still no evidence of virus-containing nanoparticles or nanoparticle transmission.

Therefore, available epidemiological implicates airborne transmission of SARS-CoV-2 as a potential route for the spreading of the disease. The possibility of long-distance aerosol transmission needs further and urgent epidemiological and experimental studies.

3.1.3. The relationship between air quality and SARS-CoV-2

Studies have shown that the high infection rate of COVID-19 is related to poor air quality (Cazzolla Gatti et al., 2020; Coccia, 2020; Conticini et al., 2020). Air pollution can cause inflammations, cell damage, and respiratory diseases (Shao et al., 2017; Feng et al., 2020; Rao et al., 2020; Wang et al., 2021). High concentrations of volatile organic compounds (VOCs) can cause health risks (Yan et al., 2015). Inflammation is the hall mark of human diseases, such as the co-morbidities (e.g., obesity) in persons that become infected with COVID-19 (Caci et al., 2020). The rise of inflammation may increase the mortality rate and the severity of expression of the disease in the most polluted areas (Comunian et al., 2020).

The positive relationship between air pollution and COVID-19 infection rate has been confirmed in many countries. For example, a study conducted in Italy showed that the infection rate of COVID-19 was associated with PM_{10} exceeding the limits in urban air (Coccia, 2020). Another study observed two regions in Europe, Lombardy, and Emilia-Romagna, which have the highest mortality rate of the virus in the World and are typified by the most polluted area in Europe (Conticini et al., 2020). Cazzolla Gatti et al. (2020) also believed that $PM_{2.5}$ was related to transmission dynamics and the infectivity of SARS-CoV-2. They projected that, with an increase of 5%–10% in air pollution, similar future pathogens may inflate the epidemic toll of Italy by 21%–32% (Cazzolla Gatti et al., 2020). In 235 Chinese cities, the relationship between short-term exposure to air pollution and daily confirmed cases were assessed, revealing a positive relationship (Zhang et al., 2021).

Other studies have shown that the concentration of air pollutants was affected by the COVID-19 lockdown. Reduction in aerosol loading over a majority of the aerosol hotspots were observed during the COVID-19 lockdown (Sanap, 2021). A study found the air pollutants PM_{10}, $PM_{2.5}$, NO_x, CO, and SO_2 decreased whereas O_3 increased in Hangzhou, China (Liu et al., 2020c). Shi et al. (2021) also observed NO_2 and $PM_{2.5}$ concentration decreased and O_3 increased in 11 cities globally with the exception of London and Paris. The lockdown not only decreased the air pollution significantly but also affected through social distancing and isolation of the COVID-19 cases from the unaffected population. A study informed that the lowest rate of COVID-19 confirmed cases were found in full lockdown (Rahman et al., 2021). The COVID-19 lockdown certainly is expected to have a synergistic effect in bringing down transmission of virus. However, more systematic epidemiological studies are needed.

Ambient PM concentrations were significantly associated with cases of human influenza and other respiratory diseases (Liang et al., 2014; Zhou et al., 2021a). Studies on COVID-19 have also shown that PM can help transmission of novel coronavirus (Barakat et al., 2020; Tung et al., 2021). PM can be exacerbated by the inflammation induced by COVID-19. Therefore, PM may play a role as a booster of COVID-19 (Mescoli et al., 2020). It is assumed that PM could be the transmission model of SARS-CoV-2 infection and could be the "carrier" of SARS-CoV-2, which enters the human body directly (Tung et al., 2021). Exposure to PM increases ACE2 expression which indirectly promotes the entry of SARS-CoV-2 into the human body (Tung et al., 2021). For SARS-CoV-2, the minimum size is approximately 60 nm (Zhu et al., 2020b). The above research stressed that the presence of ambient PM is involved in the spread of SARS-CoV-2 is crucial.

3.1.4. The survival potential of SARS-CoV-2 in the air

The survival potential and transmission routes of viruses in airborne transmission are affected by environmental factors. Studies have shown that temperature and humidity in the air, microbial resistance to external physical and biological stresses, and ultraviolet intensity all affect the viability and distribution of microorganisms in the air (Pyankov et al., 2012; Trancossi et al., 2021). An experimental study suggested that the greater the humidity, the larger the airborne particle size, and the less easy the particle diffusion (Pawar et al., 2009). Atmospheric humidity effects on viral spread have been identified by many studies, but the conclusions are still controversial. High air humidity seems to be the most important climatic factor in viral spreading in the rainforest region (Crema, 2021). In two humid regions of Iran, the rate of SARS-CoV-2 spreading is high (Ahmadi et al., 2020). However, in arid areas, humidity has a reverse relationship with the disease infection rate (Ahmadi et al., 2020). Ma et al. (2020) showed the risk of SARS-CoV-2 was inversely proportional to the relative humidity and directly proportional to the diurnal temperature range. The novel coronavirus can maintain its activity in aerosol for three hours (van Doremalen et al., 2020). The WHO pointed out that high temperature, high or low pH value and sunlight may inactivate the coronavirus (WHO, 2020b). However, in a bathroom, it was found that novel coronavirus was infective despite being in an environment with both high humidity and temperature (Luo et al., 2020). A study on the infection of COVID-19 in 122 cities in China from January to February 2020 has revealed that the infection rate did not decrease when the weather became warm (Xie and Zhu, 2020). The relationship between COVID-19 transmission parameters and environmental factors is used to elucidate whether they are related to viral mutation rate. The transmission speed of the first wave of the virus decreased with temperature, and high ultraviolet light would reduce the transmission speed, but the second wave of mutant COVID-19 adapted to a higher temperature

(Seligmann et al., 2020). Therefore, the ability of the virus to survive in the air has not yet been agreed upon, but it has been shown that the mutant virus has a higher survivability.

At present, there are still doubts about the mode of airborne transmission of novel coronavirus. Although there is growing evidence to prove the transmission route of SARS-CoV-2 in the air, further proofs are needed. Aerosol transmission could occur in some cluster cases when the environmental factors are suitable. However, understanding the outdoor transmission of aerosol is an urgent priority. In addition, to explain the relationship between air pollution and infection rate of COVID-19, the studies reviewed here demonstrate that exposure to air pollution especially $PM_{2.5}$ and PM_{10} may contribute significantly to higher rates of COVID-19. However, there are several viewpoints without reliable supporting evidence. The results of these investigations (e.g., Zhu et al., 2020a) may be affected by the issue of spurious correlation due to the omission of a common factor, namely, population density (Copiello and Grillenzoni, 2020). Therefore, human factors should be considered when evaluating the relationship between infection rate and air pollution. There have been conflicting reports on the role of temperature and humidity in the viability of novel coronavirus. Maybe global scale research will be able to allow more accurate data of larger ranges of temperature and humidity. Although there are still controversies about the airborne transmission mode and survival potential of novel coronavirus, the activity of SARS-CoV-2 in the air has been substantiated, and this mode of transmission should not be ignored.

3.2. Water transmission of SARS-CoV-2

The rapid spread of coronaviruses during outbreaks suggests the primary mode of transmission of human coronaviruses is respiratory droplets and close contact. However, their fecal elimination also suggests the possible spread via water. SARS-CoV-2 has been found in the fecal samples and anal swabs of some patients, and thus, demonstrating the possibility of fecal-oral (including waterborne, e.g., sewage pipes, wastewater, and agricultural runoff) transmission (La Rosa et al., 2020). For example, novel coronavirus RNA has been detected in the feces of symptomatic and asymptomatic COVID-19 patients (Jones et al., 2020). The scarcity of information on coronaviruses in the environment suggests that further studies are needed to understand the fate of these viruses in the water cycle.

3.2.1. Potential fecal-oral transmission

Digestive tract (Gastrointestinal tract; GIT) transmission is also known as fecal-oral transmission. Fecal-oral transmission refers to bacteria and viruses discharged from the body through excreta to pollute the environment, followed by entry into the human respiratory and/or GIT to infect patients. Numerous studies have established that the GIT is a potential transmission route of SARS-CoV-2 (Arslan et al., 2020; Chen et al., 2020c; Wu et al., 2020). It is reported that the receptor ACE2 was positively stained for gastrointestinal epithelial cells (Xiao et al., 2020). An analysis of data from COVID-19 patients in Hong Kong demonstrated that viral RNA was detected in 48.1% of the patients' fecal samples, and the fecal samples collected even after respiratory samples tested negative were still positive (Cheung et al., 2020). A similar study comparing respiratory and fecal samples from patients with SARS-CoV-2 indicated that fecal samples remained positive for an average of 27 ± 9 days after first symptom onset (i.e., an average of 11 ± 2 days longer than respiratory samples) (Wu et al., 2020). Therefore, strict precautionary measures are essential to prevent fecal transmission.

Novel coronavirus has been detected in sewage from wastewater treatment plants (e.g., Wang et al., 2020). These studies demonstrated that the novel coronavirus was able to invade the human digestive tract and utilize the fecal-oral transmission route to enter the water cycle (e.g., Arslan et al., 2020). At present, there is no direct evidence that the aerosolized SARS-CoV-2 viral particles may be contracted from domestic wastewater. However, untreated sewage water containing the virus may be a dissemination medium. Contaminated fecal particles may enter natural water bodies through leaky sewers or due to contaminated wastewater treatment plants, especially those in developing countries (Majumdar et al., 2019). Novel coronavirus in water transmission may pose several risks, including the airborne spread of virus-containing aerosols from toilet flushing by household members (Fig. 6), the contact transmission of contaminated hands and inanimate surfaces due to poor personal hygiene behaviors, and the surface contact transmission caused by arthropods (e.g., flies, cockroaches) (Arslan et al., 2020; Heller et al., 2020).

3.2.2. Wastewater monitoring as an early warning system

Novel coronavirus has been found in water sources, but there is no direct evidence to confirm whether the waterborne virus has the capacity to cause infection. However, regular wastewater monitoring can be used as a means of early warning (Foladori et al., 2020). Firstly, utilizing the concentration of the virus in a body of water, the infection level of a local population may be estimated. Secondly, because patients may defecate before symptoms appear, the virus can be detected before spreading. The study also found novel coronavirus in feces 3 days post-infection (Han et al., 2020a), but the diagnosis time of COVID-19 has been two weeks. In addition, some patients excreted SARS-CoV-2 RNA via feces post-recovery. For example, a patient's feces sample was still positive 33 days after the respiratory tract sample was negative (Wu et al., 2020). Therefore, a rigorous monitoring program for the detection of COVID-19 in wastewater could provide a way forward in terms of an advanced warning system.

3.2.3. The survival potential of SARS-CoV-2 in water

The transmission of viruses through water is not only affected by the properties of virus itself (e.g., enveloped, and lower shell disorder, Gwenzi, 2021), but also by the environmental conditions (e.g., water matrix and temperature) (Ahmed et al., 2020). The lower shell disorder of SARS-CoV-2 may lead to the possibility of fecal-oral transmission (Gwenzi, 2021). Water matrix and temperature, as the environmental conditions, can affect the viability of the virus (Table 3). A study has confirmed that at 4 °C, SARS-CoV-2 can survive for 27.8 ± 4.45 days in untreated wastewater and 43.2 ± 5.95 days in autoclaved wastewater. At 15 °C, SARS-CoV-2 can survive for 20.4 ± 2.13 days in untreated wastewater and 29.9 ± 2.39 days in autoclaved wastewater. At 25 °C, SARS-CoV-2 can survive for 12.6 ± 0.59 days in untreated wastewater and 13.5 ± 0.85 days in autoclaved wastewater. At 37 °C, SARS-CoV-2 can survive for 8.04 ± 0.23 days in untreated wastewater and 5.71 ± 0.50 days in autoclaved wastewater (Ahmed et al., 2020). For safety reasons, researchers tend to use the substitute virus including human coronaviruses (i.e., SARS-CoV-1) and other influenza viruses (i.e., Murine hepatitis virus, MHV) to conduct the experiments (Wang et al., 2005; Ahmed et al., 2020). SARS-CoV-1, which is very similar to SARS-CoV-2, is used in the experiments, and it is found that, at 4 °C, SARS-CoV-1 can survive in all types of water (domestic sewage and dechlorinated tap water) for more than 14 days. Compared to other types of water, in feces and urine, this virus can survive for more than 17 days at 4 °C, but at 20 °C, SARS-CoV-1 only can survive 3 days (Wang et al., 2005). MHV, as another similar virus, has also been used in the experiments, and it is found that, in untreated wastewater, the survival days of the viruses are different at different temperatures (Ahmed et al., 2020). Survival days are 56.6 ± 14.2 days at 4 °C,

Table 3
Environmental viability of SARS-CoV-2 and other similar viruses in different water environments.

Species of virus	Temperature (°C)	Water matrix	Survival potential	References
SARS-CoV-1	4	Feces and urine	More than 17 days	Wang et al., 2005
		All types of water	More than 14 days	
	20	Feces and urine	3 days	
SARS-CoV-2	4	Untreated wastewater	27.8 ± 4.45 days	
		Autoclaved wastewater	43.2 ± 5.95 days	
	15	Untreated wastewater	20.4 ± 2.13 days	
		Autoclaved wastewater	29.9 ± 2.39 days	
	25	Untreated wastewater	12.6 ± 0.59 days	
		Autoclaved wastewater	13.5 ± 0.85 days	
	37	Untreated wastewater	8.04 ± 0.23 days	
		Autoclaved wastewater	5.71 ± 0.50 days	
Murine hepatitis virus(MHV)	4	Untreated wastewater	56.6 ± 14.2 days	Ahmed et al., 2020
		Autoclaved wastewater	43.1 ± 4.02 days	
	15	Untreated wastewater	28.5 ± 4.43 days	
		Autoclaved wastewater	33.9 ± 1.97 days	
	25	Untreated wastewater	17.3 ± 2.46 days	
		Autoclaved wastewater	17.6 ± 2.46 days	
	37	Untreated wastewater	7.44 ± 0.61 days	
		Autoclaved wastewater	5.58 ± 0.25 days	

28.5 ± 4.43 days at 15 °C, 17.3 ± 2.46 days at 25 °C, 7.44 ± 0.61 days at 37 °C (Ahmed et al., 2020). In autoclaved wastewater, the virus has a shorter survival period. At 4 °C, MHV can survive 43.1 ± 4.0 2 days. At 15 °C, it can survive 33.9 ± 1.97 days. At 25 °C, MHV can survive 17.6 ± 2.46 days. And at 37 °C, MHV can survive 5.58 ± 0.25 days (Table 3) (Ahmed et al., 2020). From these experiments, it can be inferred that SARS-CoV-2 has a strong vitality in the water environment of low temperature, the isotonic human body, and/or wastewater.

SARS-CoV-2 in the water environment may come from untreated sewage, poorly performing sewage treatment plants, and waterworks that lack sanitation facilities. SARS-CoV-2 is an enveloped virus which can survive for several days in wastewater and surface water (Han et al., 2020a). Compared with the non-enveloped viruses (e.g., coxsackieviruses, rotavirus, or poliovirus), which can survive for extended periods on surfaces, the enveloped viruses, including H1N1 and human coronaviruses, remain infectious on surfaces after several days (Firquet et al., 2015). In contrast, the enveloped viruses have a faster inactivation rate, poorer environmental stability, and higher sensitivity to oxidants, such as chlorine (Gundy et al., 2009; Ye et al., 2016; Pinon and Vialette, 2018). Therefore, oxidant containing chlorine can be used for virus inactivation in sewage treatment plants. The method recommended by WHO is that disinfectants with chlorinated free chlorine concentration greater than 0.5 mg/l should be exposed for at least 30 min at pH 8.0 (WHO, 2020b). However, organic matters and suspended solids in the wastewater can be adhered to and protected from the virus (Pinon and Vialette, 2018). Thus, the inactivation efficiency of disinfectants can be reduced. When the viral load was high, the disinfectant might not be enough to inactivate SARS-CoV-2 (Zhang et al., 2020a). Therefore, the effective purification measures of viruses require further studies.

The novel coronavirus transmission in water takes place after the virus enters the GIT and is discharged from the body into the water source, causing the putative transmission route. At present, it is still unclear what the concentration limit of the virus is in water. At the same time, there are a limited number of studies on the survival potential of novel coronavirus in water. The risk of novel coronavirus in sewage cannot be ignored, especially in developing countries with poor sewage treatment facilities.

3.3. Soil transmission of SARS-CoV-2

Soil transmission is partly similar to the airborne transmission route, whereby contaminated soils have the potential to be resuspended and inhaled by humans and animals (Donado et al., 2021; Trejos et al., 2021). Another component of transmission is water runoff to the soil, where wastewater treatment is lacking. Untreated wastewater is used directly to irrigate the soil, or it may cause indirect diffusion of the soil near the water flow (Conde-Cid et al., 2020). Some studies are investigating the detection and quantification of SARS-CoV-2 in sewage sludge, which provides an approach to estimate changes in COVID-19 prevalence on a population level (Peccia et al., 2020). However, the infection of novel coronavirus in soil has not been proved, and the virulence of SARS-CoV-2 in sewage sludge and soil has not been determined (Collivignarelli et al., 2020). Despite this, the expression of coronavirus proteins with hydrophobic structure can bind to soil components (Zhang et al., 2020b) which may allow the coronavirus to enter the soil. After passing through 70 cm of soil in the column test and field test, fecal bacteria can still survive in leachate (Periago et al., 2002), implying that the infection of novel coronavirus in soil is possible.

The factors affecting the transmission of virus in soil mainly include soil types, temperature, and pH values (Collivignarelli et al., 2020; Nunez-Delgado, 2020; Steffan et al, 2020). However, there is a lack of data on the infectivity of SARS-CoV-2 in soil. On one hand, vitro experiments show that the resistance of SARS-CoV-2 to high temperature is decreased (Collivignarelli et al., 2020). On the other hand, it has been shown that even significant changes in pH (from 3 to 10) do not seem to confirm the disappearance of SARS-CoV-2 (Chin et al., 2020). A study examining the survival of enveloped virus (e.g., H5N1) in soil demonstrated that the virus did not survive in sandy topsoil but did survive in purchased construction sand and compost suggesting that different soil characteristics greatly impact virus survival (Steffan et al., 2020).

It is difficult to find SARS-CoV-2 RNA in different types of soil, resulting in the lack of data on the survival of SARS-CoV-2. The effective transmission ability of pathogens in soil has not been confirmed. Therefore, there is a risk of virus transmission in soil, so further research should be carried out on different types of soil receiving sewage and the different plants growing within the soil.

3.4. Biota transmission of SARS-CoV-2

Recent studies have recognized that SARS-CoV-2 can originate from biota (Rodriguez-Morales et al., 2020; Zhou and Shi, 2021). Due to the high homology between SARS-CoV-2 and bat-CoV, bats are considered as the original hosts of SARS-CoV-2, and minks, or pangolins may be intermediate hosts, albeit further investigation is needed (Luan et al., 2020; Zhang et al., 2020c). Much remains to be elucidated regarding which species may act as natural reservoirs or transmission vectors for the virus. Our current knowledge indicates that biota may play a major role in the evolution of novel coronavirus.

Biota also plays a role in the spread of novel coronavirus. Some studies have found that beetles and domestic insects are carriers of pathogens, and these insects transmit the virus by contacting contaminated surfaces and secretions of patients (Vazirianzadeh et al., 2014). At present, it has been proved that the fecal particles of patients contain SARS-CoV-2 (Wu et al., 2020). The municipal government of Guanzhou has also ordered the mass extermination of rats, cockroaches, flies, and mosquitoes, although there has been no conclusive evidence that insects are involved in the spread of SARS-CoV-1 (Parry, 2004). They can transmit more than 100 pathogens through legs, hair, oral, feces, and vomit (Hazeleger et al., 2008). Therefore, feeding domestic insects and beetles with feces may play an important role in disease spread by mechanical transmission of virus. Insects lack a receptor that can bind SARS-CoV-2, thus preventing the virus from replicating in insects (Dicke et al., 2020). However, if the domestic waste and sewage are not treated properly, the risk of mechanical transmission of SARS-CoV-2 by insects may be increased (Dehghani and Kassiri, 2020). Recently, the rapid spread of SARS-CoV-2 infection was reported in mink farms and the associated mutations resulted in a new mink-associated variant that was identified in both minks and humans, thereby providing evidence of mink-to-human transmission (Sharun et al., 2020). Measures should be taken to prevent the spread of novel coronavirus and mutant viruses. WHO has declared that mosquitoes cannot transmit SARS-CoV-2 (WHO, 2020a). Mosquitoes are not carriers of novel coronavirus, even if a small amount of virus is inhaled into mosquitoes with blood, it cannot survive and not enter saliva through the digestive system. In an experimental study of the possibility of SARS-CoV-2 infection and its ability to transmit through mosquitoes, it was revealed that SARS-CoV-2 could not replicate in these mosquitoes under extreme conditions (Huang et al., 2020b). Therefore, it is considered impossible to transmit SARS-CoV-2 to humans even when mosquitoes feed on the virus-host.

It can be summarized that biota has played a role in the evolution and transmission of novel coronavirus, and there is a close relationship between humans, animals, and the environment. Therefore, policymakers should pay attention to the cross-species transmission of SARS-CoV-2 and other potential transmission problems caused by biota.

3.5. Surface transmission of SARS-CoV-2

Coronavirus can survive on the surfaces of objects. Infection may occur when humans make contact with the surface of contaminated objects and then the mucosal parts (e.g., the oral cavity or nasal cavity) when the virus reaches a certain load. Surfaces contact usually occurs in environments involving medical treatments, visiting friends and family, and food transportation.

Frequent surface contact contamination in the medical environment is a potential source of the virus (Tran et al., 2012; Zhou et al., 2021b). A study detected SARS-CoV-2 in surface swabs collected from hospitals of Wuhan using both RT-PCR and digital PCR, and the positive detection rate was 3.1% (Zhou et al., 2021b). The viruses have also been detected in the samples collected on the surface of an ICU ventilator (Ong et al., 2020). Although the body fluids and blood of patients are contained in medical wastes, they are usually classified and incinerated by medical centers and hospitals to prevent the transmission of the virus.

With the spread of the epidemic situation and the implementation of self-segregation measures, solid waste containing surviving SARS-CoV-2 may be generated at the household level, which brings infection risk to front-line garbage disposal workers. For example, in a case study by Dhakal and Karki (2020), active surveillance and contact were traced in patients being asymptomatic in Nepal. Epidemiological studies show that the vast majority of the cases in Nepal were young males (Dhakal and Karki, 2020). The contaminated solid waste may spread to the scavengers and garbage disposal workers, resulting in the second spread of COVID-19. Additionally, some of the waste materials are sold in informal markets to poor people, posing additional risk of infection (Kharel, 2020). Therefore, it is suggested that different stages of waste management should be adopted to prevent the surface transmission of the virus (CDC, 2021). However, there is no evidence that SARS-CoV-2 is transmitted through domestic solid waste and has not attracted the attention of the scientific community.

Transmission of the virus through materials such as doorknobs, doorbells, or inhalers is crucial. Household gloves and medical mask waste also pose a risk of infection and environmental contamination (Kraay et al., 2018). Under laboratory-controlled conditions, SARS-CoV-2 on non-porous surfaces gradually lost its infectivity completely at ambient temperatures on day 4 (Ben-Shmuel et al., 2020). A similar study was carried out in another experiment in which the viability of viruses on different surfaces was assessed (Chin et al., 2020). SARS-CoV-2 was more stable on glass and paper money (4 days) and stainless steel and plastic (7 days). After 7 days of culture, detectable infectious virus levels were found on the outer layer of surgical masks (Chin et al., 2020). These studies indicated that different surfaces also affected the survival potential of the virus.

Environmental conditions may facilitate the surface transmission of the virus. Some studies have shown that relative humidity and temperature will have influences on the survival of coronavirus on inanimate surfaces (Aboubakr et al., 2020; Kratzel et al., 2020). The data showed that the survival time of some human coronaviruses was longer under low temperature and low humidity (Aboubakr et al., 2020). An experiment showed that the increase of temperature and relative humidity accelerated the inactivation of SARS-CoV-2 on the surface (Biryukov et al., 2020). Yet, a study showed that the infectivity of SARS-CoV-2 was low in the initial drying process, and the survival potential was not related to the ambient temperature (Kratzel et al., 2020). Therefore, it is still controversial whether the surface viability of novel coronavirus is related to temperature, warranting further investigations.

In general, SARS-CoV-2 RNA may be detected on many surfaces in the community and hospital where the outbreak occurred. It has been shown that viruses can exist on different surfaces, but the environmental survival conditions still need to be examined. According to this, the routes of transmission through the surface of articles are complex.

3.6. Cold-chain transmission of SARS-CoV-2

There is no evidence that the novel coronavirus can be transmitted through food, but during the current pandemic, frozen foods served as a vehicle for remote transmission (Han et al., 2020b). Since July 12, 2020, SARS-CoV-2 RNA contaminations in frozen food mostly on their packaging materials imported from the countries with ongoing epidemics have been reported in several provinces in China (Han et al., 2020b). Therefore, cold-chain transmission is a special surface propagation mode.

Novel coronavirus may cause long-distance cold-chain transmission through low temperature treatment of food, freezing storage, and the cold-chain for transporting, which seriously threatens food safety. In the Xinfadi Market of Beijing, novel coronavirus was detected on the cutting board of imported salmon, and subsequently, 40 environmental positive samples were found (Pang et al., 2020). The virus genome sequence analysis showed that the virus sequence had obvious mutation characteristics (Pang et al., 2020). The results of the epidemiological investigation showed that a single outbreak source took place in Beijing. An epidemiological investigation was conducted on the stevedores with no contact history of COVID-19 cases at Qingdao Port, and the SARS-CoV-2 was first isolated from the surface of the outer packaging of imported cod (Liu et al., 2020b). Combined with the above cases, it is inferred that the cause of the outbreak of COVID-19 may be the contamination of the external packaging of imported food during cold-chain transportation.

A recent study found that the infectivity of SARS-CoV-2 on the surface of frozen food (e.g., chicken, salmon, and pork) did not decrease after 21 days at 4 °C and –20 °C (Fisher et al., 2020). This suggested that the cold chain environment may prolong the life span of the novel coronavirus and cause secondary infection. However, since cold-chain food usually contains water, it is necessary to study the influence of the permeability of virus on the surface of substrate material on the survival time of virus.

Although it is not clear whether novel coronavirus concentrations in frozen food packaging can cause infection, there is an urgent need to curb community communication in the early days. There is a high possibility that cold-chain transmission may become a pathway of novel coronavirus transmission. Policymakers should regularly supervise and inspect the implementation of the normalization, prevention, and control measures for the novel coronavirus epidemic in the cold-chain industry, elucidate the weak links and expedite the blocking of risk points.

4. Insufficient control measures

As the survival potential of viruses in different environmental media are diverse (Table 4), our understanding of the environmental transmission of novel coronavirus is still limited, which makes the disease difficult to control. In particular, the following measures must be implemented:

(1) The survival potential of the virus in different environments requires more systematic investigations in order to facilitate our understanding of environmental transmission routes.
(2) At present, there are no proper methods to prove the transmission pathways of the viral aerosol in outdoor and fecal-oral transmission.
(3) Solid waste, biota, soil, and other environmental research fields have not received sufficient attention. Although there are a few relevant studies, additional investigations should be undertaken for these different environments.
(4) There is a lack of mathematical models to verify the relationship between novel coronavirus and environmental factors. Collaboration of scientists from different areas is necessary for this urgent task.
(5) Some research results are only a snapshot of the current situation, while the environment has a cumulative effect over a long period of time. The cumulative effects must be considered when carrying on the identification of the pathways of the SARS-CoV-2.
(6) Most of the simulation experiments used the extrapolation method, in which the viruses with similar characteristics to SARS-CoV-2 (e.g., SARS-CoV-1, murine hepatitis virus [MHV]) were used. The application of these methods is often limited by different properties and different gene sequencing of viruses.

Table 4
SARS-CoV-2 survival potential in different environments.

Environmental media	Survival potential of SARS-CoV-2 in environment
Air	SARS-CoV-2 can maintain active in the air, but its viability remains controversial. The variant of virus has higher survival ability
Water	At the low temperature, the virus can survive in human excreta, and an isotonic environment, and wastewater
Soil	There is a lack of experiments on virus survival ability in soil. Vitro experiments showed that the resistance of the virus was low under high temperature and was not affected by pH
Surface contact	Different surfaces also affected the survival potential of the virus. It is controversial whether the surface viability of virus is related to temperature
Cold-chain	The virus can survive for a long time at a low temperature

5. Conclusion and prospects

In this overview, we have summarized the potential environmental transmission routes and environmental persistence of the SARS-CoV-2 and propose some suggestions for further prevention and in-depth study. The main conclusions and prospects are as follows.

(1) The environmental transmission pathways of SARS-CoV-2 are mainly through air, water, cold-chain, and surface, with potential transmission in soil and by biota. SARS-CoV-2 RNA was detected in the air, water, sludge, and surface of the epidemic areas. Droplet transmission in the air has been identified, and aerosol and fecal-oral transmission could occur in some cluster cases.
(2) The survival potential of SARS-CoV-2 varies in the different environmental media. There is still a contradiction between the survival potential of the virus in air and/or on inanimate surfaces. Low temperature and isotonic environment are more suitable for virus to survive in water. In the cold-chain environment, SARS-CoV-2 can survive for several days at low temperatures.
(3) SARS-CoV-2 can be a biological nanoparticle on its own, which can directly enter the human body. It is possible nanoparticles at the top end of the size range could act as SARS-CoV-2 carriers to influence the spread of virus. However, a composite carrier nanoparticle + virus will be too large to be classified as a single nanoparticle. It is plausible that these composite particles could be inhaled into human lungs and then to the circulatory system causing infection.
(4) Regular environmental monitoring (e.g., air, sewage, soil) can be used to assess the future trend of COVID-19 infection, to understand the relationship between the virus and the environment, and to provide a means of early warning for potential virus outbreaks.
(5) In general, detailed research on solid waste, biota, soil, and other environments has not received sufficient attention in terms of virus transmission. More investigations should be undertaken focusing on the environmental transmission pathways of virus, which could contribute to the prevention and control of the COVID-19 epidemic.

Declaration of Competing Interest

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

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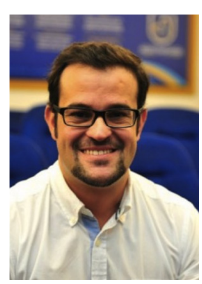

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