Multiple relationships between aerosol and COVID-19: a framework for global studies

Yaxin Cao [a], Longyi Shao [a *], Tim Jones [b], Marcos L.S. Oliveira [c,d], Shuoyi Ge [a], Xiaolei Feng [a], Luis F.O. Silva [c], Kelly BéruBé [e]

a State Key Laboratory of Coal Resources and Safe Mining and College of Geoscience and Surveying Engineering, China University of Mining and Technology (Beijing), Beijing 100083, China

b School of Earth and Environmental Sciences, Cardiff University, Cardiff, CF10, 3YE, Wales, UK

c Department of Civil and Environmental, Universidad de la Costa, Calle 58 #55-66, 080002 Barranquilla, Atlántico, Colombia

d Departamento de Ingeniería Civil y Arquitectura, Universidad de Lima, Avenida Javier Prado Este 4600 – Santiago de Surco 1503, Perú

e School of Biosciences, Cardiff University, Cardiff CF10 3AX, Wales, UK

*Corresponding author: ShaoL@cumtb.edu.cn

Abstract: COVID-19 **(**Corona Virus Disease 2019) is a severe respiratory syndrome currently causing a human global pandemic. The original virus, along with newer variants, is highly transmissible. Aerosol is a multiphase system consisting of the atmosphere with suspended solid and liquid particles, which can carry toxic and harmful substances; especially the liquid components. The degree to which aerosol can carry the virus and cause COVID-19 disease is of significant research importance. In this study, we have discussed the aerosol transmission as the pathway of SARS-CoV-2 (Severe Acute Respiratory Syndrome Coronavirus 2), and the aerosol pollution reduction as a consequence of the COVID-19 lockdown. The aerosol transmission routes of the SARS-CoV-2 can be further subdivided into proximal human-exhaled aerosol transmission and potentially more distal ambient aerosol transmission. The human-exhaled aerosol transmission is a direct dispersion of the SARS-CoV-2. The ambient aerosol transmission is an indirect dispersion of the SARS-CoV-2 in which the aerosol act as a carrier to spread the virus. This indirect dispersion can also stimulate the up-regulation of the expression of SARS-CoV-2 receptor ACE-2 (Angiotensin Converting Enzyme 2) and protease TMPRSS2 (Transmembrane Serine Protease 2), thereby increasing the incidence and mortality of COVID-19. From the aerosol quality data around the world, it can be seen that often atmospheric pollution has significantly decreased due to factors such as the reduction of traffic, industry, cooking and coal-burning emissions during the COVID-19 lockdown. The airborne transmission potential of SARS-CoV-2, the infectivity of the virus in ambient aerosols, and the reduction of aerosol pollution levels due to the lockdowns are crucial research subjects.

Keywords: COVID-19, SARS-CoV-2, transmission routes, atmospheric aerosols, $PM_{2.5}$

1. Introduction

COVID-19 (Corona Virus Disease 2019) is another infectious disease caused by coronavirus following MERS (Middle East Respiratory Syndrome) and SARS (Severe Acute Respiratory Syndrome). The number and speed of COVID-19 infections significantly exceed those of MERS and SARS (Gautam et al., 2020; Javed et al., 2020). The virus that causes COVID-19 is named SARS-CoV-2 (Severe Acute Respiratory Syndrome Coronavirus 2) (Gorbalenya et al., 2020). Since the first confirmed COVID-19 patient was identified on December 12th, 2019, the total number of patients diagnosed in the world has reached 91,293,732 cases by January 12, 2021, especially in the USA (23,143,197 cases) and India (10,479,179 cases) (https://covid19.who.int/), this number is still rapidly rising. In addition to the respiratory disease, SARS-CoV-2 can also cause other clinical symptoms, such as damage to the nervous system (Huang et al., 2020). COVID-19 has high infectivity with treatments being rapidly optimized, and it is typically most dangerous for the elderly (Pagani et al., 2020) or those with underlying health issues. Since SARS-CoV-2 was first identified a number of variants have been found in COVID-19 cases around the world (Weisblum et al., 2020), including the UK and South Africa (Koyama et al., 2020; Tang et al., 2021). Currently, the 501Y.V2 variant is considered to be a more highly transmissible strain due to the rapidity with which it became the dominant circulating genotype in South African over a few weeks (Tegally et al., 2020). Thus, the variants of SARS-CoV-2 further challenged the campaign against the COVID-19 pandemic. Studies have shown that close contact and respiratory droplets can't explain all infections (Tabatabaeizadeh, 2021), and the environmental transmissions have become an important mechanism of COVID-19 spread, such as water (Sunkari et al., 2021), aerosol (Santarpia et al., 2020), and low-temperature enhanced spread 'cold chain' (Zhang, 2020b). Among these, aerosol transmission is relatively difficult to prevent.

Aerosol is a multiphase system consisting of the atmosphere with suspended solid and liquid particles, which can carry toxic and harmful substances; especially the liquid components (Mao et al., 2002). According to their aerodynamic diameter, the airborne particles are divided into PM_{10}, $PM_{2.5}$, PM_1 and nanoparticles (Chen et al., 2020; Boongla et al., 2020). The aerosol is considered potentially harmful to human health as it can contain not only hazardous elements and chemicals (Shao et al., 2006), 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).

In such a severe COVID-19 pandemic, it is essential to study the transmission routes of this virus. According to the National Health Commission of the People's Republic of China, the main transmission routes of SARS-CoV-2 are respiratory droplets and contact transmission, and in a relatively closed environment, long-term exposure to a high concentration of aerosol may cause aerosol transmission (www.gov.cn/zhengce/zhengceku/2020-08/19/content_5535757.htm). Before the 1930s, it was thought that respiratory infectious diseases could be transmitted by airborne substances, but there was no size division of these substances (Brown and Allison, 1937; Kramer et al., 1939). With the development of aerosol detection technology, more in-depth studies have been undertaken, and droplet transmission has been subdivided into large droplets and small droplets, and the small droplets are classified as aerosol (Bourouiba, 2020). This characterization is now widely used, but the critical diameter discriminating between droplets and aerosol is variable, ranging from 5 μm to 10 μm (Bourouiba, 2020). The WHO (World Health Organization) considers 5 μm as the boundary, with the respiratory droplet having a diameter > 5 μm, and respiratory aerosol having a diameter < 5 μm (Tellier et al., 2019). Studies have shown that the large droplets are more easily dropped out of atmospheric suspension, whereas multiphase turbulent buoyant clouds, i.e., the small droplets or aerosol particles contained in a locally humid and warm atmosphere will stay airborne for a longer time (Bourouiba et al., 2014). These aerosol particles will take much longer to be removed from the atmosphere (Scharfman et al., 2016), and therefore have a greater potential to spread the virus. In addition to direct virus aerosol transmission, some virus-containing substances in the environment can generate aerosols for further transmission. For example, SARS-CoV-2 has been detected in feces and urine (Du et al., 2020; Perchetti et al., 2020), potentially allowing aerosol transmission caused by poor hygiene and practices with human excrement.

The meteorological factors such as temperature and humidity have impacts on transmission of COVID-19. It is generally accepted that a higher temperature would inactivate SARS-CoV-2 (Guo et al., 2021; Notari, 2021) and a higher humidity is associated with spreading SARS-CoV-2 (Ratnesar-Shumate et al., 2020; Crema, 2021; Fernandez-Raga et al., 2021) although there are very few cases which showed the opposite result (Ma et al., 2020). The uncertainty exists about the influence of temperature and humidity on the propagation of COVID-19, which requires more systematic investigation.

In response to the COVID-19 emergency, many countries over all the world in an attempt to curb the spread of the infection have introduced a range of social-distancing measures including shutdowns and traffic restrictions. Emission control measures initiated and enforced due to major events can have a significant effect on reducing ambient aerosol pollution. For example, after the 2008 Olympic Games and the APEC meeting and, particulate pollutant levels have been reduced (Guo et al., 2016). Air quality has also been significantly improved in Beijing in response to intensified control strategies over 2013–2019 (Shao et al., 2019; Chang et al., 2019; Li et al., 2020d). It is expected that the unprecedented pandemic lockdowns could have a considerable impact on ambient aerosol pollution.

Although some phenomena demonstrate that there are mutual relationships between SARS-CoV-2 and aerosols, the nature of these complicated relationships remains unclear. In order to provide a framework for future prevention strategies, it is necessary to study the relationship between SARS-CoV-2 and aerosols. In this review, we have considered the multiple pathways and mechanisms of aerosol on the transmission of SARS-CoV-2, as well as the possible changes to aerosol pollution as a consequence of the COVID -19 lockdowns. Along with the airborne transmission potential of SARS-CoV-2, the infectivity of the virus in ambient aerosols requires further research.

The relationship between aerosol and COVID-19 can be divided into two aspects (Figure 1). One is that SARS-CoV-2 spreads through aerosol. The other is that aerosol pollution decreased during COVID-19 lockdown. The aerosol exhaled by the COVID-19 patients can directly transmit the virus. Ambient aerosols affect the transmission of SARS-CoV-2 in two ways. One way is that ambient aerosols act as virus vectors indirectly; the other way is that ambient aerosols can stimulate the expression of SARS-CoV-2 receptor and protease, and increase the binding site of SARS-CoV-2, thus increasing the morbidity and mortality of COVID-19. As a result of the prevention and control measures during the lockdown, coupled with the self-constraint of people, human activities have been greatly reduced, which leads to a great decrease of the mass concentration of ambient aerosols.

2. Influence of human-exhaled aerosol on the transmission of COVID-19

2.1 Airborne transmission characteristics of the human-exhaled aerosol

The aerosol produced by sneezing and coughing can travel for 7-8 m (Bourouiba, 2020). In a simulation test of a Laryngo-Tracheal Mucosal Atomization Device, which enables clinicians to deliver a fine mist of atomized medication across the mucosa membrane, the upper airways and beyond the vocal cords, the aerosol produced appeared on doctors' necks, face, hands, arms, goggles, masks, and protective clothing, and also around the operating room (Endersby et al., 2020). Studies have shown that when people sneeze or cough, the droplets larger than 10 μm will sediment nearby, pollute that environment, and risk direct and indirect transmission of the virus, whereas the droplets smaller than 10 μm when leaving the airway will become droplet nuclei or aerosols (Bourouiba, 2020). These aerosols can stay airborne in the atmosphere much longer (Bourouiba, 2020), and aerosol particles with an aerodynamic diameter less than 2.5 μm can enter the alveoli directly (Feng et al., 2020). When compared with the nasal cavity and trachea, when the virus accumulates in alveoli, small doses can cause infection (Lindsley et al., 2010). In contrast to sneezing or coughing that can produce a large amount of aerosol, breathing and speaking can produce finer particles (< 1.5 μm) (Asadi et al., 2019), and these smaller aerosol particles can travel further in the air (Lindsley et al., 2014).

2.2 Evidence of human-exhaled aerosol containing SARS-CoV-2

The particle sizes of exhaled aerosol produced by COVID-19 patients during speaking and coughing ranged from < 0.25 μm (submicron) to about 10 μm, which has been shown to contain SARS-CoV-2 RNA and has the ability to transmit the virus in the air (Zou et al., 2020). Both symptomatic and asymptomatic patients have high SARS-CoV-2 viral load in their nasopharynx and trachea (Baggio et al., 2020), which provides the required conditions for exhaled aerosols to carry the virus. There are conflicting evidences for airborne transmission of SARS-CoV-2 (Falahi and Kenarkoohi, 2020). A study has detected SARS-CoV-2 virus RNA on the surface of an air vent, room air and corridor air in a COVID-19 ward (no patient cough was observed during sampling), and it is found that 63.2% of the samples were positive for SARS-CoV-2, and the concentration level reached 2420 RNA copies / m^3 (Santarpia et al., 2020). The presence of SARS-CoV-2 in aerosols was also monitored in the hospital environment, which accounted for 285-1130 RNA copies/m^3 (Zhang et al., 2020a). The viruses have also been detected in the samples collected on the surface and in the air of buses and subway trains (Moreno et al., 2020), and on the surface of an ICU ventilator (Ong et al., 2020)

Some medical procedures are more likely to produce human-exhaled aerosols. In March 2020, Public Health England defined AGP (Aerosol Generation Procedure) in the medical processes, such as intubation, dental surgery, high flow nasal oxygen and other related procedures (Simonds, 2020).

Transnasal drill and cautery use is associated with the production of the aerosol in the range of 1 to 10 um under endonasal procedures (Workman et al., 2020). The SARS-CoV-2 has been detected in the submicron and ultra-micron aerosol of two hospitals in Wuhan (Liu et al., 2020c).

SARS-CoV-2 RNA appeared inside the air conditioner and the air samplers, or on object surfaces more than 2m away from patients, within only 20 minutes after the patients registered into the ward (Santarpia et al., 2020), which shows that the airflow can take the virus aerosol particles from the patient bed to the edge of the room by ventilation. A full-scale test by (Ai et al., 2019) has revealed the transmission characteristics of the exhaled aerosol in the air and they have shown that people near the virus carriers have a relatively high exposure risk, especially those facing the infectious person. All these studies indicate that the SARS-CoV-2 infection may occur within a very short period after exposure to the COVID-19 patients.

In summary, when compared with the large droplets, the human-exhaled aerosol has a stronger diffusion ability, and similarly, the aerosols carrying SARS-CoV-2 produced by COVID-19 patients have a higher transmissibility. In addition to the contact transmission and closed airborne transmission, SARS-CoV-2 may also be transmitted by aerosols in ventilation systems. The possibility of long-distance aerosol transmission needs further and urgent epidemiological and experimental studies. Aerosols carrying SARS-CoV-2 are likely to be produced in the common treatments of cardiopulmonary, oral and airway diseases. Hospitals are densely populated environments, where strict protective measures must be implemented to ensure the safety of medical staff and other personnel.

2.3 Similarity of air transmission of SARS-CoV-2 and other viruses

Phylogenetic analysis revealed that SARS-CoV-2 and SARS-CoV (Severe Acute Respiratory Syndrome Coronavirus) are both in the subgenus *Sarbecovirus* of the genus *Betacoronavirusare* (Lu et al., 2020), and therefore SARS-CoV-2 is similar to the SARS-CoV in terms of gene sequence homology (Gorbalenya et al., 2020). On February 11th, 2020, ICTV (International Committee on Taxonomy of Viruses) stated that CSG (Coronaviridae Study Group) has recognized SARS-CoV-2 as a sister clade to SARS-CoV (Gorbalenya et al., 2020; Liu et al., 2020a). In terms of structure and function, both of them are the coronavirus associated with severe acute respiratory syndrome, and they are homologous RNA viruses that can cause human pneumonia.

Table 1 provides some comparisons between SARS-CoV-2 and SARS-CoV, which illustrates our understanding of the transmission mechanism, prevention, and treatment of COVID-19. As shown in Table 1, SARS-CoV-2 and SARS-CoV belong to the same genera *Betacoronavirus*. Both have similar diameters, with the size of SARS-CoV-2 being 65 -125 nm, and the size of SARS-CoV being 80-120 nm (Shereen et al., 2020). The host cell receptors of both SARS-CoV-2 and SARS-CoV are the ACE-2 protein, but the affinity between SARS-CoV-2 and receptor protein is higher which would facilitate a relatively fast transmission of corresponding diseases (Giron et al., 2020). van Doremalen et al. (2020) have established an experimental environment to test the stability of SARS-CoV-2 and SARS-CoV, and they have found that the survival time (aerosol half-life) of the two viruses in the air after artificial aerosolizing was similar, but the retention time of SARS-CoV-2 on the surfaces of objects was relatively longer, which increased the risk of resuspension. SARS-CoV has the known ability for airborne transmission and this virus was found in an air sampler 5 feet (1.52 m) away from the patient (Booth et al., 2005). SARS-CoV can also be transmitted between buildings (Yu et al., 2004) and aircraft passengers (Olsen et al., 2003). A study on a hospital in Beijing suggested that nosocomial, hospital-derived, infection could be the main cause of the early prevalence of SARS in the hospital (He et al., 2003).

Other coronaviruses and common viruses can also have the ability of aerosol transmission. Studies on the human coronavirus 229E (a common cold virus) have shown that the experimental virus-carrying aerosol can persist at 20°C and 50% relative humidity for 6 days (Ijaz et al., 1985). Influenza patients emit aerosol particles containing the influenza virus when they are coughing, and most of the virus RNA is incorporated into the particles within the respiratory size range (Lindsley et al., 2010). In seasonal influenza transmission, a large number of virus copies were detected in fine aerosol particles (Milton et al., 2013).

In summary, there are similarities between SARS-CoV-2 and SARS-CoV in gene sequence and stability. The SARS-CoV-2 virus, other coronaviruses and common viruses also have aerosol transmission capacity. SARS-CoV-2 can be directly transmitted through human-exhaled aerosol. In future prevention and control research, the characteristics of SARS-CoV and other viruses, especially their airborne transmission potential needs to be further elucidated.

3. Influence of ambient aerosols on the transmission of COVID-19

3.1 Epidemiological relationship between ambient aerosol and COVID-19

Long-term exposure to poor air quality can cause arrange of diseases (Guo et al., 2016). Epidemiological and *in-vitro* experimental evidence shows that aerosol pollution exposure has a positive correlation with respiratory diseases, such as COPD (Chronic Obstructive Pulmonary Disease), asthma (Kesic et al., 2012), ILI (Influenza Like Ill) (Su et al., 2019), ALI (Acute Lung Injury) (Li et al., 2019) and SARS (Yao et al., 2020).

Since the outbreak of COVID-19, scholars in many parts of the world, including Europe, North America and Asia, have undertaken studies on the epidemiological relationship between air pollution indicators and COVID-19. Konstantinoudis et al. (2020) used high-resolution hierarchical spatial analysis to investigate 38573 cases of COVID-19 deaths in 32844 small areas in England as of June 30th, 2020 and used the Bayesian hierarchical model to quantify the impact of air pollution. The results showed that the mortality of COVID-19 would increase by 1% for every 1μg/m^3 increase of NO_2 and $PM_{2.5}$. The COVID-19 cases in Germany from February 24th to July 2nd, 2020 have been examined by correlation analysis and WTC (Wavelet Transform Coherence), and it has been found that the concentrations of $PM_{2.5}$, O_3, and NO_2 were significantly associated with the prevalence of

COVID-19 (Bilal et al., 2020). The data from 55 Italian regional samples, as of April 7th, 2020 showed that the rapid spread of COVID-19 in northern Italy was highly correlated with local air pollution (Coccia, 2020). In northern Italy, the geographical factors of the local mountains and the high densities of factories and transportation were the main causes of $PM_{2.5}$, PM_{10}, NO_2 and O_3 pollution, which mirrored the higher occurrence frequency and severity of COVID-19 (Daniele and Francesco, 2020). Milan, located in the Po Valley Basin, is a recognized hot spot of aerosol pollution. Through comprehensive time series analysis, Zoran et al. (2020) found that the $PM_{2.5}$ and PM_{10} in the metropolitan area of Milan from January 1st to April 30th, 2020 were significantly positively related with the prevalence of COVID-19. The association between air quality indicators and COVID-19 cases in California was analyzed using the Spearman and Kendall correlation test, and the results indicated that ambient pollutants including the mass concentrations of PM_{10}, $PM_{2.5}$, SO_2, and NO_2 were negatively correlated with the prevalence of COVID-19 and only the CO concertation showed a positive correlation with the COVID-19 (Bashir et al., 2020). In another study in California, the time-series analysis revealed that, in addition to the CO and O_3, the concentration of $PM_{2.5}$ was also positively correlated with increases in the incidence and mortality of COVID-19 (Meo et al., 2021). A national cross-sectional study was conducted on more than 3000 counties (98% of the population) in the United States, and the results showed that the increase of $PM_{2.5}$ by only $1\mu g/m^3$ was associated with an 8% increase in the mortality rate of COVID-19 (Wu et al., 2020).

Air pollution and meteorological data have been collected from January 25th to April 7th, 2020 in Wuhan, China, and Pearson and Poisson regression models have been used to study the relationship between COVID-19 mortality and each risk factor; this research concluded that $PM_{2.5}$ was the only pollutant with positive correlation with COVID-19 mortality (Jiang and Xu, 2020).

A longitudinal cohort study of 6529 patients from 28 urban areas of Japan has been conducted, and the results showed that short-term exposure to the suspended particulates may affect respiratory tract infection caused by SARS-CoV-2 (Azuma et al., 2020). The outpatient data of 21 Japanese cities demonstrated a delayed association between $PM_{2.5}$ and cardiopulmonary examination (Seposo et al., 2020).

The positive association between aerosol and confirmed cases or deaths of COVID-19 in Zhu et al. (2020) has been questioned for lack of the study of population density (Copiello and Grillenzoni, 2020). Therefore, when we analyze the relationships between the concentrations of airborne particles and the confirmed cases or deaths of COVID-19, we shouldn't ignore the impacts from population density. The data of Bashir et al. (2020) showed the concentration of PM2.5, had a negative correlation with prevalence of COVID-19, while the study by Meo (2021) revealed a positive correlation between these two parameters. Therefore, the use of Spearman and Kendall correlation tests may not give a solid evidence, some of the associations resulted from the correlation analysis may still need to have proof from other parameters.

The results described above have been summarized in Table 2, and most of these studies have supported the hypothesis that poor air quality increases the prevalence and mortality of COVID-19. In particular, a positive relationship has been observed between $PM_{2.5}$ and COVID-19 morbidity or mortality. The consistently positive significant correlation provides further evidence that long-term exposure to relatively high concentrations of ambient aerosols is responsible for the increased transmission and pathogenicity of SARS-CoV-2 in the relevant population. Table 2 also showed the positive correlation between most gaseous pollutants and COVID-19. NO_2, SO_2, O_3 and CO may play important roles in two possible ways; one is that exposure to high levels of gaseous pollutants can cause inflammation of the airways to affect lung function and respiratory symptoms (Huang and Brown, 2021), and the other is that the secondary reaction between aerosols and gaseous pollutants will be strengthened at lower temperature and higher relative humidity condition (Ding et al., 2021), which can enhance the harm of aerosols.

It is important to study the relationship between air pollution and human health in order to help policy-makers to formulate positive strategies to reduce the pollution of ambient aerosols, especially

$PM_{2.5}$, which would help to alleviate the rapid spread of COVID-19 and, potentially, to decrease the spread of epidemic viruses and diseases in the future.

3.2 Mechanism of ambient aerosol affecting COVID-19 diffusion

3.2.1 Ambient aerosols play a role as the carrier of SARS-CoV-2

SARS-CoV-2 may enter the human body through aerosol; not only long-term but also short-term exposure will have a great adverse impact on the human immune system (Zoran et al., 2020). Although the atmospheric processes experienced by the aerosol particles after release from the human body could, to some extent, cause severe damage to SARS-CoV-2 (Zhen et al., 2013), SARS-CoV-2 can survive in aerosols for 3 hours, and can survive on the surfaces of other contact materials for even longer times, i.e. copper (3.4 hours) < cardboard (8.45 hours) < stainless steel (13.1 hours) < plastic (15.9 hours) (van Doremalen et al., 2020). Under certain conditions, viruses on the surface of objects and in water can resuspend into the air and combine with existing aerosols (Ravi et al., 2020).

Ambient aerosols play a carrier or enhancement role for SARS-CoV-2 (Martelletti and Martelletti, 2020). The morbidity and mortality of COVID-19 are related to air pollution emission sources. In addition to humans as the source of ambient aerosol transmission, TSDF (hazardous waste treatment, storage and disposal facilities) and RMP (Risk Management Plan) sites are potential air pollution sources (Hendryx and Luo, 2020; Tung et al., 2021). Under certain conditions, ambient aerosols, such as water-borne aerosols, can provide favorable surfaces for the adsorption of organic molecules and viruses, and facilitate higher transmission rate under certain ambient conditions (Manoj et al., 2020). Polluted water can be a source of viruses, and aerosols from this source can carry a variety of viruses, leading to a higher exposure rate for residents living around the contaminated area (Rocha-Melogno et al., 2020). In Australia, SARS-CoV-2 was detected in a wastewater treatment plant (Ahmed et al., 2020).

Fecal-oral transmission could be an additional route for SARS-CoV-2 spread. After the virus enters the body, the virus-specific RNA and protein are synthesized to assemble new viruses, which are then released into the gastrointestinal tract, and finally expelled from the body (Xiao et al., 2020b), so the feces of COVID-19 patients have a high viral load (Xiao et al., 2020a). Aerosols in sanitary pipeline systems can carry viruses, resulting in a higher-risk of infection (Gormley et al., 2017). It is postulated that there is a risk of SARS-CoV-2 infection through aerosol when using contaminated toilets (Wang et al., 2020b). Since fecal aerosol transmission may have caused the community outbreak of COVID-19 in high-rise buildings (Kang et al., 2020), understanding the transmission routes of aerosol-related sewage and fecal sources may be important for reducing the spread of COVID-19, especially in developing countries.

The described evidence above shows that SARS-CoV-2 can combine with ambient aerosols and enter the human body, but there is little experimental evidence about the combination of the SARS-CoV-2 and aerosols. Whether virus aerosol detected around patients are human-exhaled aerosol or ambient aerosol is worth further experimental verification.

3.2.2 Ambient aerosols can up regulate SARS-CoV-2 receptor and related protease

Aerosol pollution exposure is associated with various respiratory and cardiovascular diseases (Pun et al., 2017), and one of the mechanisms is the up-regulation of ACE-2 (Angiotensin Converting Enzyme 2) and TMPRSS2 (Transmembrane Serine Protease 2) (Lin et al., 2018). ACE-2 is the main receptor protein of SARS-CoV-2, and the synaptic glycoprotein of the virus has a high affinity for ACE-2 in host cell targets (Vankadari and Wilce, 2020). TMPRSS2 is a protease that can cleave viral spike protein and make it combine with target cells to promote infection (Hayashi et al., 2010). The up-regulation of ACE-2 is a protective mechanism when the respiratory system is exposed to aerosol, which can maintain the dynamic balance of RAS (Renin Angiotensin System) and reduce inflammatory reaction (Ye and Liu, 2020). ACE-2 is abundantly expressed not only in the lung, but also in the glandular cells of gastric, duodenal, and rectal epithelia of the patients with COVID-19 (Xiao et al., 2020b).

When $PM_{2.5}$ invades the human body, ACE-2, as the receptor for SARS-CoV-2 to enter cells, will protect against renin–angiotensin system-induced lung injuries by cleaving Angiotensin II to limit substrate availability in the adverse AEC-Ang II-Ang II receptor 1 axis (Parajuli et al., 2014). Therefore, $PM_{2.5}$ can increase the SARS-CoV-2 susceptibility for human body by enhancing the expression of AEC-2 and its cofactor TMPRSS2 (Kim et al., 2020). An in vivo experimental study has confirmed that the expression level of ACE-2 in the lung of experimental mice was significantly increased after being induced by $PM_{2.5}$ (Lin et al., 2018). Statistical analysis suggests that $PM_{2.5}$ may be the cause of the overexpression of ACE-2 in human epithelial cell surfaces of the respiratory tract (Paital and Agrawal, 2020). For smokers, a large number of aerosols with a particle size of less than 1 μm will be generated by the process of smoking. After smoking, these aerosols can be suspended in the indoor atmosphere for a long time (Cao et al., 2018), and this would impact the secondhand (passive) smokers who would also show an increase in the expression of ACE-2 in their bronchi (Aliee et al., 2020). Compared with non-smokers, the expression of ACE-2 and TMPRSS2 in smokers and patients with chronic obstructive pulmonary disease (COPD) were significantly up-regulated (Sharif-Askari et al., 2020).

Overall, there was a significant correlation between aerosol concentration level, ACE-2 expression, and severity of COVID-19 infection (Paital and Agrawal, 2020). Therefore, the decision-makers should pay particular attention to the air pollution in areas where COVID-19 is prevalent, and appropriate measures should be implemented in order to reduce this air pollution. Smoking promotes the expression of ACE-2 and TMPRSS2 in the airway. Therefore, during the pandemic, the control of smoking in public places needs more strict legislation, and non-smoking individuals should be advised to avoid proximity to smokers. It may be worthwhile to explore the therapeutic effects of recombinant ACE-2 protein in the early stage of COVID-19 infection (Li et al., 2020a).

4. Changes in aerosol pollution during COVID-19

Since Wuhan announced the implementation of COVID-19 lockdown on January 23rd, 2020, China and other regions in the world have taken measures to restrict travel and shut down industry and commerce to avoid crowd gathering and reduce the spread of COVID-19. The prevention and control measures taken by these countries have greatly reduced the transmission rates of COVID-19 (Koyama et al., 2020). With the large-scale shutdowns and traffic restrictions, the aerosol pollution had a general corresponding decrease in levels (Zhou et al., 2012; Liu et al., 2021; Shi et al., 2021). The results of aerosol concentration changes in different regions during the COVID-19 lockdown are summarized in Figure 2, which demonstrates the impact of prevention and control measures on aerosol pollution.

As shown in Figure 2, compared with the preceding period of COVID-19 lockdown, the average concentration of PM2.5 has decreased by 38% in California (Liu et al., 2020b), 21.8% in Hat Yai, Thailand (Stratoulias and Nuthammachot, 2020), 52% in Pearl River Delta (Wang et al., 2021) and 41.2% in Wuhan (Sulaymon et al., 2021) during COVID-19 lockdown, and the average concentration of PM_{10} has decreased by 31% in Barcelona, Spain (Tobias et al., 2020), 22.9% in Hat Yai, Thailand (Stratoulias and Nuthammachot, 2020) and 33.1% in Wuhan (Sulaymon et al., 2021). Compared with the preceding years, $PM_{2.5}$ and PM_{10} mass concentrations of 22 cities in India decreased by about 43% and 31% during the lockdown (Sharma et al., 2020). The $PM_{2.5}$

concentration in Almaty, Kazakhstan, during the lockdown, is 21% lower than the average level in the same period of 2018-2019 (Kerimray et al., 2020). Compared with the same period in the previous four years, the pollutants PM_{10} and $PM_{2.5}$ in Singapore decreased by 23% and 29%, respectively (Li and Tartarini, 2020a). A survey was conducted in 19 countries in the South and Southeast Asian region, compared to the same period of 2019, the $PM_{2.5}$ level decreased by an average of 20.25% (Roy et al., 2021). Compared with the same period last year, the $PM_{2.5}$ concentration in the regional Level I and Level Ⅱ response periods in the Yangtze River Delta region decreased by 33.7% and 29% respectively (Li et al., 2020c).

The large reduction of human activities has significantly improved air quality in many areas during the control of COVID-19. Compared with the pre-lockdown period, the concentrations of PM_{10} (14-20%) and $PM_{2.5}$ (7-16%) in 597 major cities in the world have decreased significantly (Liu et al., 2021). For the areas with more serious air pollution problems, the improvement of the aerosol is greater, and the decrease of $PM_{2.5}$ is greater than that of PM_{10} (Figure 2). Therefore, the decrease of air pollutants in areas with high pre-lockdown levels is more obvious, and $PM_{2.5}$ is more sensitive to emission reduction (Wang et al., 2021).

Some studies have investigated the reasons for the decrease of atmospheric aerosol concentrations. Measures such as city closure and vehicle restrictions greatly reduced the types of primary aerosols related to traffic and reduced the levels of air pollution (Liu et al., 2021; Chen et al., 2021), and at the same time, many factories shut down and stop production, and the emission of the secondary industry decreased (Wang et al., 2020c). In Beijing, the vast majority of restaurants were closed, and the aerosol emissions of cooking and gas burning decreased by 30-50% on average (Sun et al., 2020). The reduction of secondary aerosol species was very small (5-12%) (Sun et al., 2020).

These results indicate that the control of anthropogenic emissions will greatly improve air quality, but they may not be able to effectively suppress secondary aerosols under stagnant weather conditions.

The studies discussed above are mostly focused on local small-scale cases. Future research should consider expanding time and space domains, combining satellite data and monitoring station data to better characterize the change of aerosol pollution. Also, meteorological factors need to be considered when studying the impact of ambient aerosols (Daniele and Francesco, 2020). The improvement of air quality caused by the epidemic prevention measures provide reference for policy-makers to formulate measures to reduce aerosol pollution.

5. Concluding remarks

(1) The relationship between aerosols and COVID-19 can be subdivided into three types; human-exhaled aerosols directly transmitting COVID-19; COVID-19 transmitted by ambient aerosols; ambient aerosol concentrations decrease as a result of the COVID-19 lockdowns.

(2) The human-exhaled aerosol produced by breathing, speaking, and sneezing can survive for a significant time (3 hours), and the airborne transportation distance can reach 7-8 meters. The airborne transmission potential of SARS-CoV-2 must be considered in prevention and control work, and the transmission of virus aerosol should be effectively decreased by ventilation, disinfection and wearing protective devices.

(3) Overexposure to ambient aerosols can cause respiratory diseases, and ambient aerosols are associated with increased morbidity and mortality by COVID-19. Two mechanisms have been discussed in this process. Firstly, SARS-CoV-2 may combine with ambient aerosols from

contaminated sites (such as medical waste treatment sites, polluted water bodies and toilet pipes) to enter the human body. Secondly, the ambient aerosol can stimulate the expression of ACE-2 and TMPRSS2, leading to the increase of SARS-CoV-2 binding sites and the acceleration of infection efficiency. The binding mechanism, survival time and residual activity of SARS-CoV-2 in ambient aerosols need to be further studied. The infectivity of the virus in ambient aerosols should be further researched.

(4) Due to the epidemic minimizing measures during COVID-19 in numerous locations worldwide, traffic emissions and factory emissions were reduced. This has been an opportunity to observe the relationship between human factors and air quality. Compared with the same period in previous years before the epidemic, aerosol pollution, especially $PM_{2.5}$, decreased significantly. The reduction of aerosols in areas with high air pollution is more obvious, and the levels of $PM_{2.5}$ are more sensitive to emission reduction than PM_{10}.

Acknowledgments

This study is supported by the National Natural Science Foundation of China (Grant No. 42075107), the Projects of International Cooperation and Exchanges NSFC (Grant No. 41571130031) and the Yueqi Scholar fund of China University of Mining and Technology (Beijing). The authors are indebted to editor-in-chief Professor M. Santosh for his constructive discussion and comments and also for his patience in editing the paper. Two anonymous reviewers are particularly acknowledged for their critical evaluations of the manuscript.

References

Ahmed, W., Angel, N., Edson, J., Bibby, K., Bivins, A., O'Brien, J.W., Choi, P.M., Kitajima, M., Simpson, S.L., Li, J.Y., Tscharke, B., Verhagen, R., Smith, W.J.M., Zaugg, J., Dierens, L., Hugenholtz, P., Thomas, K.V., Mueller, J.F., 2020. 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. Sci. Total Environ. 728, doi:10.1016/J.SCITOTENV.2020.138764.

Ai, Z.T., Huang, T., Melikov, A.K., 2019. Airborne transmission of exhaled droplet nuclei between occupants in a room with horizontal air distribution. Build. Environ. 163, 106528.

Aliee, H., Massip, F., Qi, C.C., Stella de Biase, M., van Nijnatten, J.L., Kersten, E.T.G., Kermani, N.Z., Khuder, B., Vonk, J.M., Vermeulen, R.C.H., Neighbors, M., Tew, G.W., Grimbaldeston, M., Ten Hacken, N.H.T., Hu, S.L., Guo, Y.K., Zhang, X.Y., Sun, K., Hiemstra, P.S., Ponder, B.A., Makela, M.J., Malmstrom, K., Rintoul, R.C., Reyfman, P.A., Theis, F.J., Brandsma, C.A., Adcock, L., Timens, W., Xu, C.J., van den Berge, M., Schwarz, R.F., Koppelman, G.H., Nawijn, M.C., Faiz, A., 2020. Determinants of SARS-CoV-2 receptor gene expression in upper and lower airways. MedRxiv: the Preprint Server for Health Sciences, doi: 10.1101/2020.08.31.20169946.

Asadi, S., Wexler, A.S., Cappa, C.D., Barreda, S., Bouvier, N.M., Ristenpart, W.D., 2019. Aerosol emission and superemission during human speech increase with voice loudness. Sci Rep 9, 2348.

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. Environ. Res. 190, 110042.

Baggio, S., L'Huillier, A.G., Yerly, S., Bellon, M., Wagner, N., Rohr, M., Huttner, A., Blanchard-Rohner, G., Loevy, N., Kaiser, L., Jacquerioz, F., Eckerle, I., 2020. SARS-CoV-2 viral load in the upper respiratory tract of children and adults with early acute COVID-19. Clin. Infect. Dis. doi:10.1093/cid/ciaa1157.

Bashir, M.F., Ma, B.J., Bilal, Komal, B., Bashir, M.A., Farooq, T.H., Iqbal, N., Bashir, M., 2020. Correlation between environmental pollution indicators and COVID-19 pandemic: A brief study in Californian context. Environ Res 187. doi:10.1016/j.envres.2020.109652

Bilal, Bashir, M.F., Benghoul, M., Numan, U., Shakoor, A., Komal, B., Bashir, M.A., Bashir, M., Tan, D., 2020. Environmental pollution and COVID-19 outbreak: insights from Germany. Air Qual. Atmos. Health, 13 (11), 1385-1394.

Boongla, Y., Chanonmuang, P., Hata, M., Furuuchi, M., Phairuang, W., 2020. The characteristics of carbonaceous particles down to the nanoparticle range in Rangsit city in the Bangkok Metropolitan Region, Thailand. Environ. Pollut. (Barking, Essex: 1987), 115940-115940.

Booth, T.F., Kournikakis, B., Bastien, N., Ho, J., Kobasa, D., Stadnyk, L., Li, Y., Spence, M., Paton, S., Henry, B., Mederski, B., White, D., Low, D.E., McGeer, A., Simor, A., Vearncombe, M., Downey, J., Jamieson, F.B., Tang, P., Plummer, F., 2005. Detection of airborne severe acute respiratory syndrome (SARS) coronavirus and environmental contamination in SARS outbreak units. J. Infect. Dis. 191, 1472-1477.

Bourouiba, L., 2020. Turbulent gas clouds and respiratory pathogen emissions: Potential implications for reducing transmission of COVID-19. JAMA-J. Am. Med. Assoc. 323, 1837-1838.

Bourouiba, L., Dehandschoewercker, E., Bush, J.W.M., 2014. Violent expiratory events: on coughing

and sneezing. J. Fluid Mech. 745, 537-563.
Brown, W.A., Allison, V.D., 1937. Infection of the air of scarlet-fever wards with Streptococcus pyogenes. The Journal of Hygiene 37, 1-13.
Cao, X.W., Zhou, Z.X., Zhang, H., Hu, X.Q., Bao, l.F., 2018. Influence of smoking on indoor air fine particle concentration. Journal of Green Science and Technology, 24, 25-27. (In Chinese with English abstract)
Chang, L.L., Shao, L.Y., Yang, S.S., Li, J., Zhang, M.Y., Feng, X.L., Li, Y.W., 2019. Study on variation characteristics of $PM_{2.5}$ mass concentrations in Beijing after the action on comprehensive control of air pollution. Journal of Mining Science and Technology 4, 539-546. (In Chinese with English abstract)
Chen, H.L., Li, C.P., Tang, C.S., Lung, S.C.C., Chuang, H.C., Chou, D.W., Chang, L.T., 2020. Risk assessment for people exposed to $PM_{2.5}$ and constituents at different vertical heights in an urban area of Taiwan. Atmosphere 11 (11), 1145.
Chen, Z.F., Hao, X.Y., Zhang, X.Y., Chen, F.L., 2021. Have traffic restrictions improved air quality? A shock from COVID-19. J. Clean Prod. 279, 123622.
Crema, E., 2021. The SARS-CoV-2 outbreak around the Amazon rainforest: The relevance of the airborne transmission. Sci. Total Environ. 759, 144312-144312.
Coccia, M., 2020. Factors determining the diffusion of COVID-19 and suggested strategy to prevent future accelerated viral infectivity similar to COVID. Sci. Total Environ. 729, 138474.
Copiello, S., Grillenzoni, C., 2020. The spread of 2019-nCoV in China was primarily driven by population density. Comment on "Association between short-term exposure to air pollution and COVID-19 infection: Evidence from China" by Zhu et al. Sci. Total Environ. 744, 141028.
Daniele, F., Francesco, R., 2020. Role of the chronic air pollution levels in the COVID-19 outbreak risk in Italy. Environ. Pollut 264, 114732.
Ding, J., Dai, Q., Zhang, Y., Xu, J., Huangfu, Y., Feng, Y., 2021. Air humidity affects secondary aerosol formation in different pathways. Sci. Total Environ. 759, 143540-143540.
Ding, J., Zhu, T., 2003. Heterogeneous reactions on the surface of fine particles in the atmosphere. Chin. Sci. Bull. 48, 2267-2276.
Du, W.J., Yu, J.H., Liu, X.Y., Chen, H., Lin, L.B., Li, Q., 2020. Persistence of SARS-CoV-2 virus RNA in feces: A case series of children. J. Infect. Public Health 13, 926-931.
Endersby, R.V.W., Ho, E.C.Y., Spencer, A.O., Goldstein, D.H., Schubert, E., 2020. Barrier devices for reducing aerosol and droplet transmission in COVID-19 patients: Advantages, disadvantages, and alternative solutions. Anesth. Analg. 131, E121-E123.
Falahi, S., Kenarkoohi, A., 2020. Transmission routes for SARS-CoV-2 infection: review of evidence. New Microbes New Infect 38, 100778.
Feng, X.L., Shao, L.Y., Xi, C.X., Jones, T., Zhang, D.Z., Bérubé, K., 2020. Particle-induced oxidative damage by indoor size-segregated particulate matter from coal-burning homes in the Xuanwei lung cancer epidemic area, Yunnan Province, China. Chemosphere 256, 127058.
Fernandez-Raga, M., Diaz-Marugan, L., Garcia Escolano, M., Bort, C., Fanjul, V., 2021. SARS-CoV-2 viability under different meteorological conditions, surfaces, fluids and transmission between animals. Environ. Res. 192, 110293.
Gautam, A., Kaphle, K., Shrestha, B., Phuyal, S., 2020. Susceptibility to SARS, MERS, and COVID-19 from animal health perspective. Open veterinary journal 10, 164-177.
Giron, C.C., Laaksonen, A., da Silva, F.L.B., 2020. On the interactions of the receptor-binding

domain of SARS-CoV-1 and SARS-CoV-2 spike proteins with monoclonal antibodies and the receptor ACE2. Virus Res. 285,198021.

Gorbalenya, A.E., Baker, S.C., Baric, R.S., de Groot, R.J., Drosten, C., Gulyaeva, A.A., Haagmans, B.L., Lauber, C., Leontovich, A.M., Neuman, B.W., Penzar, D., Perlman, S., Poon, L.L.M., Samborskiy, D.V., Sidorov, I.A., Sola, I., Ziebuhr, J., Coronaviridae Study, G., 2020. The species Severe acute respiratory syndrome-related coronavirus: classifying 2019-nCoV and naming it SARS-CoV-2. Nat. Microbiol. 5, 536-544.

Gormley, M., Aspray, T.J., Kelly, D.A., Rodriguez-Gil, C., 2017. Pathogen cross-transmission via building sanitary plumbing systems in a full scale pilot test-rig. Plos One 12 (2), e0171556.

Guo, C., Bo, Y., Lin, C., Li, H.B., Zeng, Y., Zhang, Y., Hossain, M.S., Chan, J.W.M., Yeung, D.W., Kwok, K.-O., Wong, S.Y.S., Lau, A.K.H., Lao, X.Q., 2021. Meteorological factors and COVID-19 incidence in 190 countries: An observational study. The Science of the total environment 757, 143783-143783.

Guo, Q., Shao, L.Y., Wang, W.H., Hou, C., Zhao, C.M., Xing, J.P., Ma, S.M., 2016. Oxidative capacity of the PM_{10} and $PM_{2.5}$ in Beijing during 2014 APEC. Environmental Science 37, 3708-3713. (In Chinese with English abstract)

Han, Y.P., Li, L., Wang, Y., Ma, J.W., Li, P.Y., Han, C., Liu, J.X., 2021. Composition, dispersion, and health risks of bioaerosols in wastewater treatment plants: A review. Front. Env. Sci. Eng. 15 (3), 38.

Hayashi, N., Yamamoto, K., Ohishi, M., Tatara, Y., Takeya, Y., Shiota, A., Oguro, R., Iwamoto, Y., Takeda, M., Rakugi, H., 2010. The counterregulating role of ACE2 and ACE2-mediated angiotensin 1-7 signaling against angiotensin II stimulation in vascular cells. Hypertens. Res., 1182-1185.

He, Y., Jiang, Y., Xing, Y.B., Zhong, G.L., Wang, L., Sun, Z.J., Jia, H., Chang, Q., Wang, Y., Ni, B., Chen, S.P., 2003. Preliminary result on the nosocomial infection of severe acute respiratory syndrome in one hospital of Beijing. Chinese Journal of Epidemiology 24, 554-556.

Hendryx, M., Luo, J., 2020. COVID-19 prevalence and fatality rates in association with air pollution emission concentrations and emission sources. Environ. Pollut. 265, 115126.

Huang, P., Tang, L., Ren, Y., Liu, L., 2020. Research progress in nervous system damage caused by SARS-CoV-2. Journal of Central South University (Medical Science), 1247-1254. (In Chinese with English abstract)

Huang, G.W., Brown, P.E., 2021. Population-weighted exposure to air pollution and COVID-19 incidence in Germany. Spat. Stat. 41, 100480-100480.

Ijaz, M.K., Brunner, A.H., Sattar, S.A., Nair, R.C., Johnson-Lussenburg, C.M., 1985. Survival characteristics of airborne human coronavirus 229E. J. Gen. Virol. 66 (Pt 12), 2743-2748.

Javed, M., Javed, F., Ergin, H.E., Maung, T.Z., Khan, S., 2020. Do COVID-19 and SARS gene complexities and variations help overcome the knowledge gap? Cureus 12, e8439-e8439.

Jiang, Y., Xu, J., 2020. The association between COVID-19 deaths and short-term ambient air pollution/meteorological condition exposure: A retrospective study from Wuhan, China. Air Qual. Atmos. Health, 1-5 (3), 46.

Kang, M., Wei, J.J., Yuan, J., Guo, J.X., Zhang, Y.T., Hang, J., Qu, Y.B., Qian, H., Zhuang, Y., Chen, X.G., Peng, X., Shi, T.X., Wang, J., Wu, J., Song, T., He, J.F., Li, Y.G., Zhong, N.S., 2020. Probable Evidence of Fecal Aerosol Transmission of SARS-CoV-2 in a High-Rise Building. Ann. Intern. Med. 173, 974-+.

Kerimray, A., Baimatova, N., Ibragimova, O.P., Bukenov, B., Kenessov, B., Plotitsyn, P., Karaca, F., 2020. Assessing air quality changes in large cities during COVID-19 lockdowns: The impacts of traffic-free urban conditions in Almaty, Kazakhstan. Sci. Total Environ. 730, 139179.

Kesic, M.J., Meyer, M., Bauer, R., Jaspers, I., 2012. Exposure to ozone modulates human airway protease/antiprotease balance contributing to increased influenza a infection. Plos One 7 (4), e35108.

Kim, J.H., Kim, J., Kim, W.J., Choi, Y.H., Yang, S.R., Hong, S.H., 2020. Diesel Particulate Matter 2.5 Induces Epithelial-to-Mesenchymal Transition and Upregulation of SARS-CoV-2 Receptor during Human Pluripotent Stem Cell-Derived Alveolar Organoid Development. Int. J. Environ. Res. Public Health. 17 (22), 8410.

Konstantinoudis, G., Padellini, T., Bennett, J.E., Davies, B., Ezzati, M., Blangiardo, M., 2020. Long-term exposure to air-pollution and COVID-19 mortality in England: a hierarchical spatial analysis. Environ. Int. 146:106316.

Koyama, T., Platt, D., Parida, L., 2020. Variant analysis of SARS-CoV-2 genomes. Bull. World Health Organ. 98, 495-504.

Kramer, S.D., Hoskwith, B., Grossman, L.H., 1939. Detection of the virus of poliomyelitis in the nose and throat and gastro-intestinal tract of human beings and monkeys. The Journal of experimental medicine 69, 49-67.

Li, J.Y., Tartarini, F., 2020a. Changes in air quality during the COVID-19 lockdown in Singapore and associations with human mobility trends. Aerosol Air Qual. Res. 20, 1748-1758.

Li, L., Huang, Q., Wang, D.C., Ingbar, D.H., Wang, X., 2020b. Acute lung injury in patients with COVID-19 infection. Clin. Transl. Med. 10, 20-27.

Li, L., Li, Q., Huang, L., Wang, Q., Zhu, A., Xu, J., Liu, Z., Li, H., Shi, L., Li, R., Azari, M., Wang, Y., Zhang, X., Liu, Z., Zhu, Y., Zhang, K., Xue, S., Ooi, M.C.G., Zhang, D., Chan, A., 2020c. Air quality changes during the COVID-19 lockdown over the Yangtze River Delta Region: An insight into the impact of human activity pattern changes on air pollution variation. Sci. Total Environ. 732, 139282.

Li, W.J., Shao, L.Y., Wang, W.H., Li, H., Wang, X.M., Li, Y.W., Li, W.J., Jones, T., Zhang, D.Z., 2020d. Air quality improvement in response to intensified control strategies in Beijing during 2013-2019. Sci. Total Environ. 744, 140776.

Li, Y.S., Dong, T.C., Jiang, X.P., Wang, C.M., Zhang, Y., Li, Y.Z., Zheng, G.H., Li, X.H., Bai, J.W., Li, H.Q., 2019. Chronic and low-level particulate matter exposure can sustainably mediate lung damage and alter CD4 T cells during acute lung injury. Mol. Immunol. 112, 51-58.

Lin, C.L., Tsai, C.H., Sun, Y.L., Hsieh, W.Y., Lin, C., Chen, C.Y., Lin, C.S., 2018. Instillation of particulate matter 2.5 induced acute lung injury and attenuated the injury recovery in ACE2 knockout mice. Int. J. Biol. Sci. 14, 253-265.

Lindsley, W.G., Blachere, F.M., Thewlis, R.E., Vishnu, A., Davis, K.A., Cao, G., Palmer, J.E., Clark, K.E., Fisher, M.A., Khakoo, R., Beezhold, D.H., 2010. Measurements of airborne influenza virus in aerosol particles from human coughs. Plos One 5, e15100.

Lindsley, W.G., Noti, J.D., Blachere, F.M., Szalajda, J.V., Beezhold, D.H., 2014. Efficacy of face shields against cough aerosol droplets from a cough simulator. J. Occup. Environ. Hyg. 11, 509-518.

Liu, F., Wang, M.C., Zheng, M.N., 2021. Effects of COVID-19 lockdown on global air quality and health. Sci. Total Environ. 755, 142533.

Liu, L., Zhang, J., Du, R.G., Teng, X.M., Hu, R., Yuan, Q., Tang, S.S., Ren, C.H., Xin, H., Xu, L., Zhang, Y.X., Zhang, X.Y., Song, C.B., Liu, B., Lu, G.D., Shi, Z.B., Li, W., 2020a. Chemistry of atmospheric fine particles during the COVID‐19 pandemic in a megacity of Eastern China. Geophys. Res. Lett. doi:10.1029/2020GL091611.

Liu, Q., Harris, J.T., Chiu, L.S., Sun, D.L., Houser, P.R., Yu, M.Z., Duffy, D.Q., Little, M.M., Yang, C.W., 2020b. Spatiotemporal impacts of COVID-19 on air pollution in California, USA. Sci. Total Environ. 750, 141592-141592.

Liu, Y., Ning, Z., Chen, Y., Guo, M., Liu, Y.L., Gali, N.K., Sun, L., Duan, Y.S., Cai, J., Westerdahl, D., Liu, X.J., Xu, K., Ho, K.f., Kan, H.D., Fu, Q.Y., Lan, K., 2020c. Aerodynamic analysis of SARS-CoV-2 in two Wuhan hospitals. Nature 582 (7813), 557-+.

Lu, R.J., Zhao, X., Li, J., Niu, P.H., Yang, B., Wu, H.L., Wang, W.L., Song, H., Huang, B.Y., Zhu, N., Bi, Y.H., Ma, X.J., Zhan, F.X., Wang, L., Hu, T., Zhou, H., Hu, Z.H., Zhou, W.M., Zhao, L., Chen, J., Meng, Y., Wang, J., Lin, Y., Yuan, J.Y., Xie, Z.H., Ma, J.M., Liu, W.J., Wang, D.Y., Xu, W.B., Holmes, E.C., Gao, G.F., Wu, G.Z., Chen, W.J., Shi, W.F., Tan, W.J., 2020. Genomic characterisation and epidemiology of 2019 novel coronavirus: implications for virus origins and receptor binding. Lancet 395, 565-574.

Ma, Y.L., Zhao, Y.D., Liu, J.T., He, X.T., Wang, B., Fu, S.H., Yan, J., Niu, J.P., Zhou, J., Luo, B., 2020. Effects of temperature variation and humidity on the death of COVID-19 in Wuhan, China. Sci. Total Environ. 724, 138226.

Manoj, M.G., Satheesh Kumar, M.K., Valsaraj, K.T., Sivan, C., Vijayan, S.K., 2020. Potential link between compromised air quality and transmission of the novel corona virus (SARS-CoV-2) in affected areas. Environ. Res. 190, 110001.

Mao, J.T., Zhang, J.H., Wang, M.H., 2002. Summary comment on research of atmospheric aerosol in China. Acta Meteorologica Sinica, 625-634. (In Chinese with English abstract)

Martelletti, L., Martelletti, P., 2020. Air pollution and the novel COVID-19 disease: a putative disease risk factor. SN Compr Clin Med. 1-5.

Meo, S.A., Abukhalaf, A.A., Alomar, A.A., Alessa, O.M., Sami, W., Klonoff, D.C., 2021. Effect of environmental pollutants $PM_{2.5}$, carbon monoxide, and ozone on the incidence and mortality of SARS-CoV-2 infection in ten wildfire affected counties in California. Sci. Total Environ. 757, 143948-143948.

Milton, D.K., Fabian, M.P., Cowling, B.J., Grantham, M.L., McDevitt, J.J., 2013. Influenza virus aerosols in human exhaled breath: particle size, culturability, and effect of surgical masks. PLoS Pathog. 9, e1003205.

Morello, T.F., 2021. COVID-19 and agricultural fire pollution in the Amazon: Puzzles and solutions. World Dev. 138, 105276.

Moreno, T., Pinto, R.M., Bosch, A., Moreno, N., Alastuey, A., Minguillon, M.C., Anfruns-Estrada, E., Guix, S., Fuentes, C., Buonanno, G., Stabile, L., Morawska, L., Querol, X., 2020. Tracing surface and airborne SARS-CoV-2 RNA inside public buses and subway trains. Environ. Int.international 147, 106326-106326.

Notari, A., 2021. Temperature dependence of COVID-19 transmission. Sci. Total Environ. 763, 144390-144390.

Olsen, S.J., Chang, H., Cheung, T.Y., Tang, A.F., Fisk, T.L., Ooi, S.P., Kuo, H., Jiang, D.D., Chen, K., Lando, J., Hsu, K., Chen, T., Dowell, S.F., 2003. Transmission of the severe acute

respiratory syndrome on aircraft. N. Engl. J. Med. 349, 2416-2422.
Ong, S.W.X., Tan, Y.K., Sutjipto, S., Chia, P.Y., Young, B.E., Gum, M., Lau, S.K., Chan, M., Vasoo, S., Mendis, S., Toh, B.K., Leong, J., Barkham, T., Ang, B.S.P., Tan, B.H., Leo, Y.S., Marimuthu, K., Wong, M.S.Y., Ng, O.T., 2020. Absence of contamination of personal protective equipment (PPE) by severe acute respiratory syndrome coronavirus 2 (SARS-CoV-2). Infect. Control Hosp. Epidemiol. 41, 614-616.
Pagani, G., Conti, F., Giacomelli, A., Bernacchia, D., Rondanin, R., Prina, A., Scolari, V., Gandolfi, C.E., Castaldi, S., Marano, G., Ottomano, C., Boracchi, P., Biganzoli, E., Galli, M., 2020. Seroprevalence of SARS-CoV-2 significantly varies with age: Preliminary results from a mass population screening. J. Infect. 81 (6), E10-E12.
Paital, B., Agrawal, P.K., 2020. Air pollution by NO_2 and $PM_{2.5}$ explains COVID-19 infection severity by overexpression of angiotensin-converting enzyme 2 in respiratory cells: a review. Environ. Chem. Lett. 1-18.
Parajuli, N., Ramprasath, T., Patel, V.B., Wang, W., Putko, B., Mori, J., Oudit, G.Y., 2014. Targeting angiotensin-converting enzyme 2 as a new therapeutic target for cardiovascular diseases. Can. J. Physiol. Pharmacol. 92, 558-565.
Perchetti, G.A., Nalla, A.K., Huang, M.L., Zhu, H.Y., Wei, Y.L., Stensland, L., Loprieno, M.A., Jerome, K.R., Greninger, A.L., 2020. Validation of SARS-CoV-2 detection across multiple specimen types. J. Clin. Virol. 128, 104438-104438.
Pun, V.C., Kazemiparkouhi, F., Manjourides, J., Suh, H.H., 2017. Long-term $PM_{2.5}$ exposure and respiratory, cancer, and cardiovascular mortality in older US adults. Am. J. Epidemiol. 186, 961-969.
Ratnesar-Shumate, S., Williams, G., Green, B., Krause, M., Holland, B., Wood, S., Bohannon, J., Boydston, J., Freeburger, D., Hooper, I., Beck, K., Yeager, J., Altamura, L.A., Biryukov, J., Yolitz, J., Schuit, M., Wahl, V., Hevey, M., Dabisch, P., 2020. Simulated sunlight rapidly inactivates SARS-CoV-2 on surfaces. J. Infect. Dis. 222, 214-222.
Ravi, S., Li, J.R., Meng, Z.J., Zhang, J.G., Mohanty, S., 2020. Generation, resuspension, and transport of particulate matter from biochar-amended soils: a potential health risk. Geohealth 4 (11), e2020GH000311.
Rocha-Melogno, L., Ginn, O., Bailey, E.S., Soria, F., Andrade, M., Bergin, M.H., Brown, J., Gray, G.C., Deshusses, M.A., 2020. Bioaerosol sampling optimization for community exposure assessment in cities with poor sanitation: A one health cross-sectional study. Sci. Total Environ. 738, 139495.
Roy, S., Saha, M., Dhar, B., Pandit, S., Nasrin, R., 2021. Geospatial analysis of COVID-19 lockdown effects on air quality in the South and Southeast Asian region. Sci. Total Environ., 144009-144009.Santarpia, J.L., Rivera, D.N., Herrera, V.L., Morwitzer, M.J., Creager, H.M., Santarpia, G.W., Crown, K.K., Brett-Major, D.M., Schnaubelt, E.R., Broadhurst, M.J., Lawler, J.V., Reid, S.P., Lowe, J.J., 2020. Author Correction: Aerosol and surface contamination of SARS-CoV-2 observed in quarantine and isolation care. Sci Rep. 10, 13892.
Scharfman, B.E., Techet, A.H., Bush, J.W.M., Bourouiba, L., 2016. Visualization of sneeze ejecta: steps of fluid fragmentation leading to respiratory droplets. Exp. Fluids 57, 9.
Seposo, X., Ueda, K., Sugata, S., Yoshino, A., Takami, A., 2020. Short-term effects of air pollution on daily single- and co-morbidity cardiorespiratory outpatient visits. Sci. Total Environ. 729, 138934-138934.

Shao, L.Y., Chang, L.L., Zhang, M.Y., Li, J., Li, Y.W., Li, W.J., Feng, X.L., 2019. Trace element compositions in $PM_{2.5}$ after the action for comprehensive control of air pollution in Beijing. Earth Science Frontiers 26, 298-308. (In Chinese with English abstract)

Shao, L.Y., Shi, Z.B., Jones, T.P., Li, J.J., Whittaker, A.G., Bérubé, K.A., 2006. Bioreactivity of particulate matter in Beijing air: Results from plasmid DNA assay. Sci. Total Environ. 367, 261-272.

Sharif-Askari, N.S., Sharif-Askari, F.S., Alabed, M., Temsah, M.H., Al Heialy, S., Hamid, Q., Halwani, R., 2020. Airways expression of SARS-CoV-2 receptor, ACE2, and TMPRSS2 is lower in children than adults and increases with smoking and COPD. Mol.Ther.-Methods Clin. Dev. 18, 1-6.

Sharma, S., Zhang, M., Anshika, Gao, J., Zhang, H., Kota, S.H., 2020. Effect of restricted emissions during COVID-19 on air quality in India. Sci. Total Environ. 728, 138878.

Shereen, M.A., Khan, S., Kazmi, A., Bashir, N., Siddique, R., 2020. COVID-19 infection: Origin, transmission, and characteristics of human coronaviruses. J. Adv. Res. 24, 91-98.

Shi, Z.B., Song, C.B., Liu, B.W., Lu, G.D., Xu, J.S., Van Vu, T., Elliott, R.J.R., Li, W.J., Bloss, W.J., Harrison, R.M., 2021. Abrupt but smaller than expected changes in surface air quality attributable to COVID-19 lockdowns. Sci. Adv. 7, eabd6696.

Simonds, A.K., 2020. 'Led by the science', evidence gaps, and the risks of aerosol transmission of SARS-CoV-2. Resuscitation 152, 205-207.

Stratoulias, D., Nuthammachot, N., 2020. Air quality development during the COVID-19 pandemic over a medium-sized urban area in Thailand. Sci. Total Environ. 746, 141320.

Su, W., Wu, X.G., Geng, X.Y., Zhao, X.D., Liu, Q., Liu, T., 2019. The short-term effects of air pollutants on influenza-like illness in Jinan, China.. BMC Public Health 19 (1), 1319.

Sulaymon, I.D., Zhang, Y.X., Hopke, P.K., Zhang, Y., Hua, J.X., Mei, X.D., 2021. COVID-19 pandemic in Wuhan: Ambient air quality and the relationships between criteria air pollutants and meteorological variables before, during, and after lockdown. Atmos. Res. 250, 105362-105362.

Sun, Y.L., Lei, L., Zhou, W., Chen, C., He, Y., Sun, J.X., Li, Z.J., Xu, W.Q., Wang, Q.Q., Ji, D.S., Fu, P.Q., Wang, Z.F., Worsnop, D.R., 2020. A chemical cocktail during the COVID-19 outbreak in Beijing, China: Insights from six-year aerosol particle composition measurements during the Chinese New Year holiday. Sci. Total Environ. 742, 140739.

Sunkari, E.D., Korboe, H.M., Abu, M., Kizildeniz, T., 2021. Sources and routes of SARS-CoV-2 transmission in water systems in Africa: Are there any sustainable remedies? Science of the Total Environment 753, 142298.

Tabatabaeizadeh, S.-A., 2021. Airborne transmission of COVID-19 and the role of face mask to prevent it: a systematic review and meta-analysis. Eur. J. Med. Res. 26, 1.

Tang, J.W., Toovey, O.T.R., Harvey, K.N., Hui, D.D.S., 2021. Introduction of the South African SARS-CoV-2 variant 501Y.V2 into the UK. J. Infect. https://doi.org/10.1016/j.jinf.2021.1001.1007.

Tegally, H., Wilkinson, E., Giovanetti, M., Iranzadeh, A., Fonseca, V., Giandhari, J., Doolabh, D., Pillay, S., San, E.J., Msomi, N., Mlisana, K., von Gottberg, A., Walaza, S., Allam, M., Ismail, A., Mohale, T., Glass, A.J., Engelbrecht, S., Van Zyl, G., Preiser, W., Petruccione, F., Sigal, A., Hardie, D., Marais, G., Hsiao, M., Korsman, S., Davies, M.-A., Tyers, L., Mudau, I., York, D., Maslo, C., Goedhals, D., Abrahams, S., Laguda-Akingba, O., Alisoltani-Dehkordi, A., Godzik, A., Wibmer, C.K., Sewell, B.T., Lourenço, J., Alcantara, L.C.J., Pond, S.L.K., Weaver, S., Martin, D., Lessells, R.J., Bhiman, J.N., Williamson, C., de Oliveira, T., 2020. Emergence and rapid spread of a new severe acute respiratory syndrome-related coronavirus 2 (SARS-CoV-2) lineage with multiple spike mutations in South Africa. MedRxiv: the Preprint Server for Health Sciences, https://doi.org/10.1101/2020.1112.1121.2024864.

Tellier, R., Li, Y.G., Cowling, B.J., Tang, J.W., 2019. Recognition of aerosol transmission of infectious agents: a commentary. BMC Infect. Dis. 19, 101.

Tobias, A., Carnerero, C., Reche, C., Massague, J., Via, M., Minguillon, M.C., Alastuey, A., Querol, X., 2020. Changes in air quality during the lockdown in Barcelona (Spain) one month into the SARS-CoV-2 epidemic. Sci. Total Environ. 726, 138540.

Tung, N.T., Cheng, P.-C., Chi, K.-H., Hsiao, T.-C., Jones, T., BéruBé, K., Ho, K.-F., Chuang, H.-C., 2021. Particulate matter and SARS-CoV-2: A possible model of COVID-19 transmission. Sci. Total Environ. 750, 141532.

van Doremalen, N., Bushmaker, T., Morris, D.H., Holbrook, M.G., Gamble, A., Williamson, B.N., Tamin, A., Harcourt, J.L., Thornburg, N.J., Gerber, S.I., Lloyd-Smith, J.O., de Wit, E., Munster, V.J., 2020. Aerosol and surface stability of SARS-CoV-2 as compared with SARS-CoV-1. N. Engl. J. Med. 382, 1564-1567.

Vankadari, N., Wilce, J.A., 2020. Emerging COVID-19 coronavirus: glycan shield and structure prediction of spike glycoprotein and its interaction with human CD26. Emerg. Microbes Infect., 601-604.

Wang, D.M., Zhou, M., Nie, X.Q., Qiu, W.H., Yang, M., Wang, X., Xu, T., Ye, Z., Feng, X.B., Xiao, Y., Chen, W.H., 2020a. Epidemiological characteristics and transmission model of Corona Virus Disease 2019 in China. J. Infect. 80, E25-E27.

Wang, S.Y., Zhang, Y.L., Ma, J.L., Zhu, S.Q., Shen, J.Y., Wang, P., Zhang, H.L., 2021. Responses of decline in air pollution and recovery associated with COVID-19 lockdown in the Pearl River Delta. Sci. Total Environ. 756, 143868-143868.

Wang, X., Han, J., Lichtfouse, E., 2020b. Unprotected mothers and infants breastfeeding in public amenities during the COVID-19 pandemic. Environ. Chem. Lett. 18, 1447-1450.

Wang, Y., Yuan, Y., Wang, Q., Liu, C., Zhi, Q., Cao, J., 2020c. Changes in air quality related to the control of coronavirus in China: Implications for traffic and industrial emissions. Sci. Total Environ. 731, 139133.

Weisblum, Y., Schmidt, F., Zhang, F.W., DaSilva, J., Poston, D., Lorenzi, J.C., Muecksch, F., Rutkowska, M., Hoffmann, H.H., Michailidis, E., Gaebler, C., Agudelo, M., Cho, A., Wang, Z.J., Gazumyan, A., Cipolla, M., Luchsinger, L., Hillyer, C.D., Caskey, M., Robbiani, D.F., Rice, C.M., Nussenzweig, M.C., Hatziioannou, T., Bieniasz, P.D., 2020. Escape from neutralizing antibodies by SARS-CoV-2 spike protein variants. eLife 9, e61312.

Workman, A.D., Jafari, A., Welling, D.B., Varvares, M.A., Gray, S.T., Holbrook, E.H., Scangas, G.A., Xiao, R., Carter, B.S., Curry, W.T., Bleier, B.S., 2020. Airborne aerosol generation during endonasal procedures in the era of COVID-19: Risks and recommendations. Otolaryngol. Head Neck Surg. 163, 465-470.

Wu, X., Nethery, R.C., Sabath, B.M., Braun, D., Dominici, F., 2020. Exposure to air pollution and COVID-19 mortality in the United States: A nationwide cross-sectional study. MedRxiv: the Preprint Server for Health Sciences doi:10.1101/2020.04.05.20054502.

Xiao, F., Sun, J., Xu, Y.H., Li, F., Huang, X.F., Li, H.Y., Zhao, J.X., Huang, J.C., Zhao, J.C., 2020a.

Infectious SARS-CoV-2 in Feces of Patient with Severe COVID-19. Emerg. Infect. Dis 26, 1920-1922.
Xiao, F., Tang, M.W., Zheng, X.B., Liu, Y., Li, X.F., Shan, H., 2020b. Evidence for Gastrointestinal Infection of SARS-CoV-2. Gastroenterology 158, 1831-+.
Yao, Y., Pan, J.H., Wang, W.D., Liu, Z.X., Kan, H.D., Qiu, Y., Meng, X., Wang, W.B., 2020. Association of particulate matter pollution and case fatality rate of COVID-19 in 49 Chinese cities. Sci. Total Environ. 741, 140396.
Ye, R.S., Liu, Z.W., 2020. ACE2 exhibits protective effects against LPS-induced acute lung injury in mice by inhibiting the LPS-TLR4 pathway. Exp. Mol. Pathol. 113.
Yu, I.T.S., Li, Y.G., Wong, T.W., Tam, W., Chan, A.T., Lee, J.H.W., Leung, D.Y.C., Ho, T., 2004. Evidence of airborne transmission of the severe acute respiratory syndrome virus. N. Engl. J. Med. 350, 1731-1739.
Zhang, R.Y., Li, Y.X., Zhang, A.L., Wang, Y., Molina, M.J., 2020a. Identifying airborne transmission as the dominant route for the spread of COVID-19. Proc. Natl. Acad. Sci. U. S. A. 117, 14857-14863 https://doi.org/10.1002/er.4919.
Zhang, X. R., 2020b. COVID-19 transmission in cold chain: A safe and green new-generation cold chain is demanded. Int. J. Energy Res. doi: 10.1002/er.6357.
Zhen, H.J., Han, T., E, F.D., Gediminas, M., 2013. Release of free DNA by membrane-impaired bacterial aerosols due to aerosolization and air sampling. Appl. Environ. Microbiol. 79 (24), 7780-7789.
Zhou, Y., Cheng, S.Y., Liu, L., Chen, D.S., 2012. A coupled MM5-CMAQ modeling system for assessing effects of restriction measures on PM_{10} pollution in Olympic city of Beijing, China. J. Environ. Inform. 19, 120-127.
Zoran, M.A., Savastru, R.S., Savastru, D.M., Tautan, M.N., 2020. Assessing the relationship between surface levels of $PM_{2.5}$ and PM_{10} particulate matter impact on COVID-19 in Milan, Italy. Sci. Total Environ. 738, 139825.
Zou, L.R., Ruan, F., Huang, M.X., Liang, L.J., Huang, H.T., Hong, Z.S., Yu, J.X., Kang, M., Song, Y.C., Xia, J.Y., Guo, Q.F., Song, T., He, J.F., Yen, H.L., Peiris, M., Wu, J., 2020. SARS-CoV-2 viral load in upper respiratory specimens of infected patients. N. Engl. J. Med. 382, 1177-1179.
Zhu, Y., Xie, J., Huang, F., Cao, L., 2020. Association between short-term exposure to air pollution and COVID-19 infection: Evidence from China. Sci. Total Environ. 727, 138704.

Figures

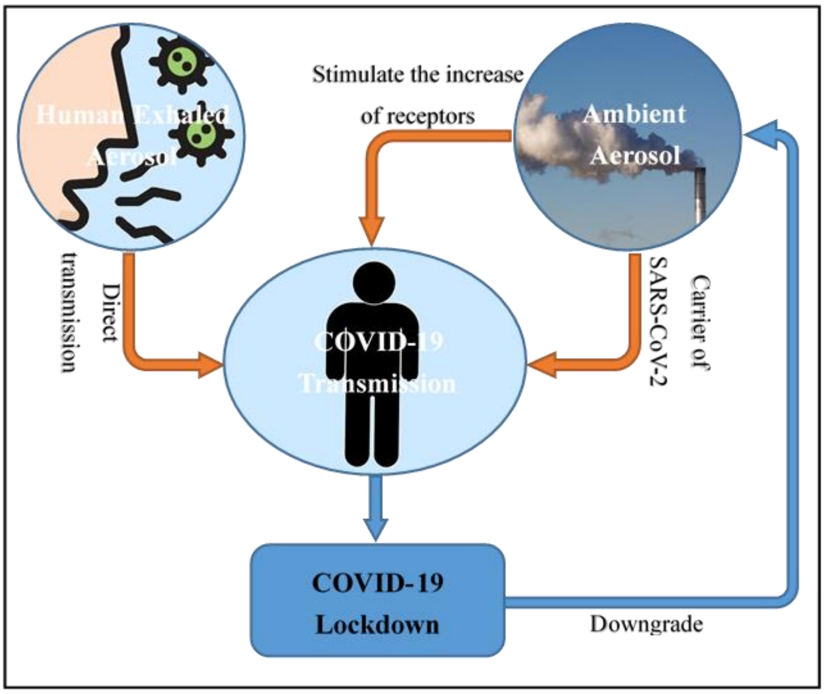

Fig. 1 The relationship between aerosol and SARS-CoV-2

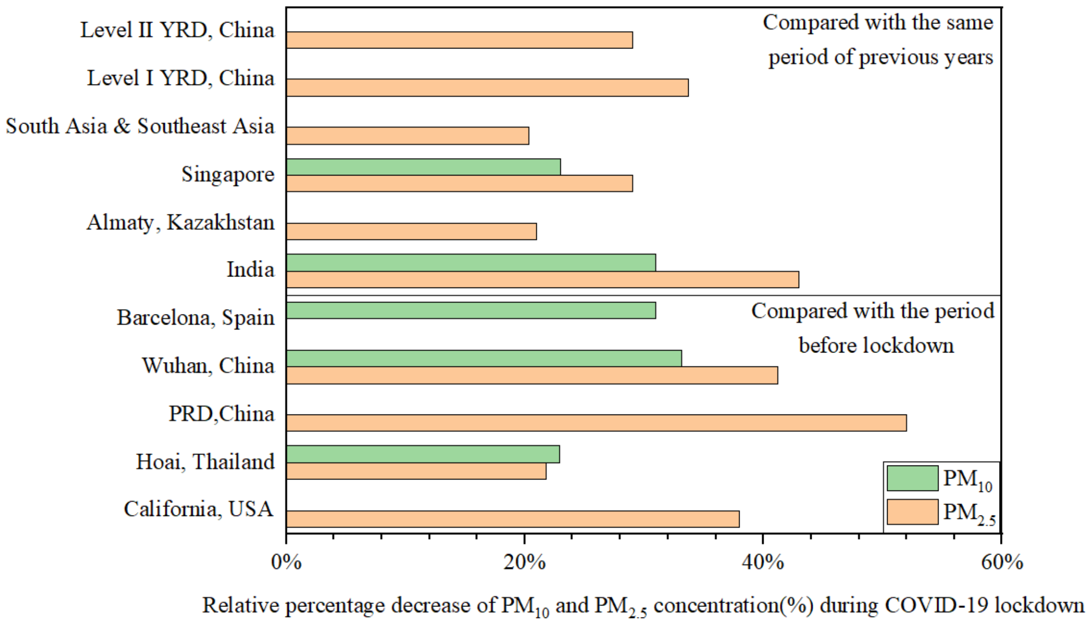

Fig. 2 The decline in concentrations of $PM_{2.5}$ and PM_{10} in various regions during COVID-19 lockdown

Tables

Table 1 Comparison of SARS-CoV-2 and SARS-CoV

Properties	SARS-CoV-2	SARS-CoV	References
Genus	*Betacoronavirus*	*Betacoronavirus*	Lu et al. 2020
Species	*Severe acute respiratory syndrome-related coronavirus*	*Severe acute respiratory syndrome-related coronavirus*	Lu et al. 2020
Size	65-125 nm	80-120 nm	Shereen et al. 2020
The receptor of the host cell	ACE-2（Higher affinity）	ACE-2	Giron et al. 2020
Infection rate	Relatively fast	Relatively slow	Wang et al. 2020a
Half-life period on aerosol	0.64-2.64 hours	0.78-2.43 hours	van Doremalen et al. 2020

Table 2 Studies showing associations of air quality indicators with the COVID-19 in different regions of the world

Region	$PM_{2.5}$	PM_{10}	NO_2	SO_2	CO	O_3	References
England	+ (uncertain)	+	+	+	+		Konstantinoudis et al., 2020
Germany	+		+			+	Bilal et al., 2020
Italy	+	+	+			+	Daniele and Francesco, 2020
Milan, Italy	+	+					Zoran et al., 2020
California, USA	+				+	+	Meo et al., 2021
California, USA	-	-	-	-	+		Bashir et al., 2020
USA	+						Wu et al., 2020
Wuhan, China	+	-		-	-		Jiang and Xu, 2020
Japan	+						Azuma et al., 2020
Japan	+						Seposo et al., 2020

Note: ‘+’ stands for promoting effect or positive correlation, ‘-’ stands for negative correlation, and blank space represents no research.