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Short communication

Potential link between compromised air quality and transmission of the novel corona virus (SARS-CoV-2) in affected areas

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ABSTRACT

The emergence of a novel human corona virus disease (COVID-19) has been declared as a pandemic by the World Health Organization. One of the mechanisms of airborne transmission of the severe acute respiratory syndrome - corona virus (SARS-CoV-2) amid humans is through direct ejection of droplets via sneezing, coughing and vocalizing. Nevertheless, there are ample evidences of the persistence of infectious viruses on inanimate surfaces for several hours to a few days. Through a critical review of the current literature and a preliminary analysis of the link between SARS-CoV-2 transmission and air pollution in the affected regions, we offer a perspective that polluted environment could enhance the transmission rate of such deadly viruses under moderate-to-high humidity conditions. The aqueous atmospheric aerosols offer a conducive surface for adsorption/absorption of organic molecules and viruses onto them, facilitating a pathway for higher rate of transmission under favourable environmental conditions. This mechanism partially explains the role of polluted air besides the exacerbation of chronic respiratory diseases in the rapid transmission of the virus amongst the public. Hence, it is stressed that more ambitious policies towards a cleaner environment are required globally to nip in the bud what could be the seeds of a fatal outbreak such as COVID-19.

1. Introduction

The first pneumonia cases of unknown origin were identified in Wuhan, the capital city of Hubei province of China in early December 2019. Further, the pathogen was identified as a novel enveloped RNA beta coronavirus, and was named Severe Acute Respiratory Syndrome Corona Virus 2 (SARS-CoV-2), which has a phylogenetic similarity to SARS-CoV. The World Health Organization (WHO) has declared corona virus disease 2019 (COVID-19) a public health emergency of international concern (Huang et al., 2020). Reports indicate that this virus started spreading globally at a fast rate and all nations are now adopting strict control measures to contain this disease by imposing lock-down of their borders and closing airports and internal transport networks. This virus is primarily transmitted through the respiratory droplets ejected from infected patients through coughing and sneezing that spread through air. Once they are released, the survival time of this virus on different surfaces essentially depend on the electrostatic interaction which play a crucial role in the effective transmission of this potential threat to human existence (Vasickova et al., 2010). The primary mode of human-to-human transmission of the epidemic caused by SARS-CoV-2 is facilitated via droplets, contaminated hands or surfaces (Kampf et al., 2020). Nevertheless, environmental surfaces also have been recognized as contributors to the transmission of various infectious viruses (Casa-nova et al., 2010). Europe and USA are the continents where casualties have been reported high of which Italy and Spain are the worst affected countries in Europe. Seasonal respiratory infections pose a major threat to human health as a result of frequent social contact and rapid genetic evolution of microbes (Chen et al., 2020a,b). Many in the society who have compromised immune systems and underlying health issues (e.g. diabetes, hypertension etc.) are easily susceptible to the disease. Many reasons are being investigated as to the mechanism of action of the virus on human respiratory elements.

Viruses are the causative agents of about 60% of human infections worldwide (Vasickova et al., 2010). Nevertheless, there is significant disagreement between the theory and empirical understanding in the medical community with regard to transmission modes of some
respiratory infections (Liu et al., 2017). Recent studies on the transmission of epidemics have pointed out several routes from a source patient: the vital role of social interaction via direct physical contact, short range airborne route (Chen et al., 2020b), and transmission through inanimate surfaces (Vasickova et al., 2016; Kampf et al., 2020). Another study by Liu et al. (2017) explored the proximity effect of close contact through substantial increase in airborne exposure to droplets nuclei exhaled by a source mankin when a susceptible mannequin was within 1.5 m of the source. They proposed that in addition to the conventional large droplet route and the short-range airborne mode by droplet nuclei, the direct deposition of droplets on other body surfaces has a significance role in spreading. In a case study (Yan et al., 2018), it is found that virus in exhaled breath of symptomatic influenza are associated with infectious aerosols that humans generate. Mathematical models that are used to estimate the contribution of each mode of transmission are sensitive to estimates of unmeasured parameters such as the viral load in exhaled breath and coughs, and the frequency of sneezing by influenza cases (Atkinson and Wein, 2008; Spicknall et al., 2010). A very reliable study (van Doremalen et al., 2020) published in February 2020. Though India has reported only 606 confirmed cases, the two Indian states, namely Maharshatra and Kerala, have the highest known spread of the epidemic. In this paper, we overview the global situation with a special focus on the South Indian state of Kerala because of two major reasons: (i) having a high population density (>860 per km$^2$) with a high percentage of emigrants (~10% of the total population) frequently visiting their homeland, and (ii) maintaining a standard of living and health care virtually equal to that of the developed countries. The climate of Kerala is tropical in nature with predominant easterlies in winter (Jan–Feb) and pre-monsoon seasons (March through May), and south-westeries during monsoon (June through September).

In the following sections, we enumerate various factors that contribute to virus spread via air pollutants, and reveal the effect of meteorological factors, in addition to formulating a hypothesis that enhanced air pollution could expedite the transmission of viruses by facilitating a conducive surface for adhesion and transport.

2. Role of air pollution in the rapid spread of COVID-19

2.1. a. Air pollution scenario in affected regions with special reference to Kerala, India

Air pollution poses a major threat to human respiratory health and kills more than 7 million people annually all over the world (WHO). This silent poisoning is facilitated by a variety of pollutant components such as particulate matter (PM$_{10}$, PM$_{2.5}$), surface ozone (O$_3$), oxides of nitrogen (NOx), carbon monoxide (CO), sulphur dioxide (SO$_2$) etc. (Source: https://www.health.nsw.gov.au/environment/air/Page s/common-air-pollutants.aspx). A multitude of studies have reported their health effects such as upper and lower respiratory track infections, irritation to eyes, nose and throats, worsening asthma and leading to chronic bronchitis, cardiovascular diseases, premature child birth and deaths, increased rate of disease progression and reduction in life expectancy (WHO, 2007). In the ongoing saga of COVID-19 infections, it has been generally observed that the level of air pollution is much higher over the fast spreading regions of COVID-19. Analysis of the air quality index (AQI, Fig. S1, acquired on 16$^{th}$ March 2020) reveals that the affected countries or regions had witnessed enhanced level of pollution (frequently AQI > 100) which are qualified as “unhealthy” and even “hazardous”, in the cold winter period. France, for example, had a worse air quality as evident from Fig. S1 (mostly unhealthy and moderate AQI). Both short-term and long-term exposure to such polluted environment could worsen the lung functionality and affect even the lower respiratory tract which can act as a platform for COVID infection for all age groups.

Fig. 1 shows the Aerosol Optical Depth (AOD, which is a direct measure of the quantum of particulate matter present in the atmosphere) obtained from the Ozone Monitoring Instrument (OMI) at 483.5 nm over Kerala, a South Indian state, during the first half of March 2020 which reveals that moderate pollution existed, especially over the southern districts of Kerala. As this region is influenced by the wind from neighbouring land mass regions in winter, the pollution level is much higher than all other seasons (Nishanth et al., 2012). Since winds during this season are directed from the east and north-east, transporting the dust and other pollutants from the southern parts of Deccan plateau, moderately larger values of AOD (>0.8, refer Fig. 1) are observed over the southern parts of Kerala State which is depicted by HYSPLIT back trajectory (https://www.ready.noaa.gov/HYSPLIT_traj.php) of air mass during this period (Fig. 2). As per the notification of Kerala Government Health Department, the first spell of transmission was identified over the southern region followed by the northern districts of Kerala state. Though, the seeds of this virus in the state is traced back to foreign origin through the frequent visits of expatriates, we believe that the swift transmission was partially facilitated by the worsening air quality over this region. This is supported by the fact that the number of symptomatic cases reported was higher (140) for the middle and southern districts of Kerala compared to the northern districts (85; see Fig. S2).

2.2. b. Polluted air affecting respiratory functionality

Increasing numbers of vehicles on the national highways provide three-dimensional corridors of smoke which contains oxides of nitrogen and black carbon. Subsequently, ground level ozone (O$_3$) is produced as a result of the photoysis of oxides of nitrogen by wavelengths less than 420 nm present in solar radiation in a rich environment of VOCs (Baylon et al., 2018), which is one of the primary species that can initiate Chronic Obstructive Pulmonary Disease (COPD) and Asthma due to its strong oxidative capacity. Thus, the possibility of COVID-19 susceptibility is much higher in those who are already exposed to oxidants in polluted areas. Further, enhanced intensity of solar ultraviolet radiation that reaches the ground in winter is the best natural viricidal agent, which primarily targets viral nucleic acid but also modifies capsid proteins. Since UV index is much higher in Kerala (>10) in a polluted environment, the elevated levels of ground level ozone produced would further deteriorate air quality by which it infects the lungs to make a supporting platform for virus infection (Gerba et al., 2002; Hjien et al., 2006; Tseng and Li, 2007). PM$_{2.5}$ species are directly inhaled into the lungs and create lower respiratory infections which also can aggravate the chances of lung infection of all age groups. Despite the fact that children are highly susceptible to respiratory problems due to air pollution, they are generally not affected by COVID-19. It may be attributed to several factors. As per our social convention, children are always kept away from the patients who are the main sources of transmission. It could also be that children are less frequently symptomatic and obviously they are less often tested (Bi et al., 2020). One of the primary observations is that immune responses of children may evolve over time to time. However, children under 3 years and children with heart diseases are mostly affected. For elders, who are always susceptible to virus attack, are infected from indirect mingling with patients who did not show any symptoms within the incubation period. Based on currently available information and clinical expertise, elder adults and people of any age who have serious underlying medical conditions might be at higher risk for severe illness from COVID-19.
2.3. c. Air pollutants offering a surface for adhesion to facilitate quick transmission of viruses

Dust particles suspended in air offer a facile surface for any virus. Being a colloidal one, the virus can interact with the surface of the dust particle and this interaction varies with the environmental temperature and humidity. Adsorption of virus to the host surface primarily depends on the isoelectric point which is a measure of pH through charge interaction between the surfaces of contact. It was reported that viruses with a low isoelectric point appear to be more poorly adsorbed to most solid surfaces. This is quite important in determining the transport of viruses in the environment. It is well known that viral attachment to surfaces occur mainly through weak van der Waals forces and also through ionic covalent bonds (Gerba, 1984). Aerosols in the atmosphere have significant quantities of water associated with them and play a major role in the transport of a variety of pollutants, particles, bacteria and viruses (Donaldson and Valsaraj, 2010). In the atmosphere, dry aerosols that are mostly hydrophilic tend to attract water and grow to larger sizes under favourable humidity conditions. Subsequently they adsorb materials like hydrophobic compounds and viruses on their air-water interface, while at the same time dissolve gases and vapor from the atmosphere into the liquid phase. The thermodynamics of this phenomenon is well understood in the literature (Valsaraj, 2009).

Recent studies indicate that viruses can survive for a prolonged period of time at a low temperature and can be transmitted to a susceptible population via different environmental media including surfaces. There is also a recent report that airborne viral RNA can be shed to the air and remain attached to many surfaces in a hospital environment (Santarpia et al., 2020). No reports show the sensitivity of corona virus sustainability with temperature. But the general understanding is that increase in environmental temperature slows down the formations of intermediate surface layers between virus and host surface (Stern Layer and Gouy Layer). Valsaraj (2012) reported that water either plays the role of a competitive adsorbate, or acts as a substrate to provide the surface area for its reaction with aerosols. The water content of the aerosol is primarily determined by environmental factors such as the type of condensation nucleus (CN), the relative humidity, temperature, and oxidation state of molecules on the surface of the aerosol. This water film on the surface of aerosols can provide a platform for the RNA rich viruses if they are hydrophilic in nature.

Fig. 1. Aerosol Optical Depth (at 483.5 nm) obtained from OMI for Kerala region during 01–20 March 2020.
A close investigation of the geographical region where the COVID-19 hit critically shows that in highly polluted regions of countries like China, northern parts of Italy, Spain and USA, the spread of COVID-19 has been quite rapid. In India, states like Maharashtra and Kerala were badly hit from the first spell. It is observed that during the early transmission stage in Italy and Spain, the pollution was higher as revealed by the satellite (Copernicus Sentinel-5P) image of European Space Agency. In Kerala, there were moderate-to-high pollution especially towards the southern part (Fig. 1) where the number of reported cases were high as per the State health department. However, a recently published work by Bontempi (2020) shows that the Italian cities that presented the higher airborne particulate matter concentrations show lower infections cases in comparison to other cities that had lower amount of this pollutant suggesting that this issue must be better investigated in the near future using laboratory experiments.

2.4. d. Rapid reduction in pollutants after complete lock-down

Recent satellite (Copernicus Sentinel-5P) images from the European Space Agency reveal that the corona virus response over the globe has, in general, reduced the air pollution emission in the affected areas, mainly over the Europe (Italy), USA and China (Figs. S4 and S5). Due to a complete lock-down to contain the disease, all the anthropogenic activities including the traffic and industrial activities have been curtailed drastically. Fig. S4(a) represents the global map of AOD while S4(b) portrays the difference between AOD during outbreak and lock-down period. Evidently, there is a substantial reduction in particulate matter over the hotspot regions of outbreak (>0.2 reduction in AOD over Europe) during the lock-down period. Italy, especially northern parts of Italy, had witnessed the greatest confirmed cases of COVID-19 except China, and a dramatic drop in pollution (Fig. S5) is thought to have a

Fig. 2. HYSPLIT back trajectory of air mass ending at 12 UTC on 01 March 2020, at three height levels of 1000, 2000, and 3000 m above ground level.
partial impact in the form of a reduction in the rapid spread of the disease in the coming days, if other causative factors remain nearly unchanged. The authors speculate that the cold weather prevailing over the region together with winds directed from the west and the adjoining seas had facilitated a conducive atmosphere for the rapid transmission of viruses through enhanced pollutants. However, as suggested by recent literature, enhanced surface temperature and UV index could, to some extent, prevent the exponential transmission expected otherwise.

3. Role of environmental factors in regulating the transmission

3.1. Role of temperature, humidity and UV index

Most respiratory viral infections have seasonal variations due to meteorological controls (Price et al., 2019). In temperate regions, the frequency of upper respiratory tract infection remains high in autumn through winter. The effect of climatic conditions on host resistance to infection, the influence of meteorological parameters on virus survival and hence on infection rate, the effect of behavioural changes etc. have been proposed for the increase in infection rate (Price et al., 2019). Bukhari and Jameel (2020) suggested the role of environmental factors in the spread of COVID-19, and observed that the transmission is high in low temperature and low absolute humidity. Other studies (Brassey et al., 2020; Sajadi et al., 2020) also have pointed out similar results of the influence of air temperature and absolute humidity on the transmission of COVID-19. Chen et al., (2020a, b) suggests the crucial role of air temperature and humidity on the spread of this deadly virus. Araújo and Naimi (2020) points to the fact that given the climatic conditions, there is a possibility of emergence of an asynchronous seasonal outbreak globally in cold climate regions which are most likely to be affected, while the tropics would be affected marginally. Wang et al. (2020) reports that high temperature and high humidity may slow down the transmission of COVID-19. Here, we make a preliminary analysis of the mean condition and variation in temperature, relative humidity and wind speed over Kerala for the period January to mid-March in 2020, wherein the role of humidity as humidifying agent of aerosols is explored.

Temperature is one of the most important parameters that determine survival of any virus in the environment. Recent studies indicate that noroviruses can survive for a prolonged period of time at a low temperature and can be transmitted to a susceptible population via different environmental media including surfaces (Mattison et al., 2007).

It is reported that viruses with single-stranded nucleic acid (ssDNA and ssRNA) are more susceptible to UV inactivation than those with double-stranded nucleic acid, and viruses with higher lipid content tend to be more persistent at a lower RH, whilst those with lesser or no lipid content are more stable at a higher RH (Vasickova et al., 2010). COVID-19 virus is classified as a member of the β group of corona viruses with an average size ranging between 65 and 125 nm in diameter. Many researchers speculated that COVID-19 has fairly high lipid content but with an average size ranging between 0.3 and 3 m s\(^{-1}\). This reduced wind speed is thought to have facilitated reduced dispersion of pollutants over the southern region of Kerala. Ultraviolet radiation is the crucial viricidal agent which lowers the virus activity, primary targets viral nucleic acid but also modifies capsid proteins. Virus resistance to UV exposure also appears to vary according to virus type. Viruses with single-stranded nucleic acid (ssDNA and

![Fig. 3. Variation in temperature (°C), relative humidity (%) and wind speed (m s\(^{-1}\)) from 01st Jan to 14th Mar 2020.](image-url)
ssRNA) are more susceptible to UV inactivation than viruses with double-stranded nucleic acid: dsDNA and dsRNA. COVID-19 being a single stranded one, UV radiation can modulate its transfer.

South India is now experiencing intense solar insolation in cloud free environment by which the UV index is more than 10 (Fig. 4). It is believed that the intense UV radiation reaching on the surface could deactivate the virus (Diffey, 1991; WHO, 2020). However, caution is invited in this regard as studies on effect of UV-B on SARS-CoV is still underway. But the dust loading (AOD) in the atmosphere can reduce UV flux due to scattering by which UV flux reduces on the ground. Accordingly, aerosol loading in the atmosphere can change virus activity. Likewise, the photolysis of pollutant gases also reduces the UV flux reaching on the ground. In an environment with high temperature and UV index, the surface ozone, a strong oxidant, will be much higher at regions away from coastal locations and can slow down the transmission. This is evident from Fig. S3, wherein enhanced ground-level ozone is observed over Kerala during the lock-down period compared to the pre-lock down period. The mean value of ozone before the lock-down was $17.9 \pm 3.22$ ppbv, and that during lock-down is $23.44 \pm 3.04$ ppbv (highlighted in red), which indicates an increase of ~31% ozone during the lock-down phase.

Thus air quality is considered to be a prime factor for the transmission of this virus once it is seeded, and the rate of transmission in Wuhan, China and Korea currently being under control may be attributed to the rapid decline in air pollution (Fig. S4) which reduces the particulates offering surfaces to transfer, and relatively high solar UV flux to slow down the virus activity. In the case of Kerala, our hypothesis of the effect of air pollution on COVID-19 transmission holds valid as evident from Fig. 5a. The social spread was rapid in Kerala in the initial outbreak period which coincides with moderate to high pollution level in the atmosphere (area averaged AOD>0.8). However, subsequent to the lock-down (marked by the red circles) initiated by the government, the pollution level came down (AOD<0.8) and the number of infection cases also showed a decreasing trend. However, here we want to point out that though there was a complete lock down, all anthropogenic activities other than domestic heating have been drastically curtailed. A good correlation ($r = 0.76$ at 10% statistical significance) is obtained between AOD and the number of affected cases of SARS-COV-2 in the State with a lag of 7 days as the approximate incubation period (refer Fig. 5a). Nonetheless, the non-linearity in the relation could be induced by changes in other controlling factors such as direct and secondary contacts, meteorological conditions, etc. A similar result is obtained from the correlation analysis (shown in Fig. 5b) wherein a moderate relation is observed between PM$_{2.5}$ and the number of COVID infected cases reported from China for the period 25th January to 30th April 2020. A moderate correlation value of 0.54 (at 10% significance level) is
obtained with a lag of 7 days of incubation period, which reveals a reasonable agreement between polluted air and the number of infections. The data for the pre-lock down period is shown by black circles whereas those during the lock-down period is depicted as red circles.

Based on the actual COVID-19 cases and the concentration of PM$_{10}$ air pollutants, a recent study by Setti et al. (2020) reports that air pollutants measured over Italy (PM$_{10}$ and PM$_{2.5}$) have a substantial influence on the COVID-19 transmission and infection rate there. Another study conducted over England confirms a positive relation between poor air quality (ozone, nitrogen oxides etc.) and death rates, after adjusting for population density (Travaglio et al., 2020). They conclude that the levels of some air pollutants are linked to COVID-19 cases and morbidity. Several other studies also point to the hostile role of air pollution either directly or indirectly on the virus transmission (Lei et al., 2018; Santarpia et al., 2020; Dutheil et al., 2020). Even though the lock down had reduced air pollution and caused a decline in cases, the authors argue strongly that air pollution has an effect on the spread of the disease through the mechanisms discussed above. Hence the present study, being preliminary in nature, calls for laboratory measurements at different pollution and environmental conditions to substantiate the given results.

In summary, higher temperature and high UV index could have prevented the exponential growth of COVID-19 cases in Kerala, even under moderate-to-high humid and polluted environmental condition. However, high population density and increased number of expatriates frequently transiting homeland during the summer vacation had triggered fast transmission of COVID-19 in this south Indian State of Kerala. Nevertheless, early warning, precaution and stringent proactive measures implemented by the Government at various levels have curbed the epidemic from spreading in to an irreparable manner. The lock-out declared by the Government of India could effectively isolate the country which could prevent the seeding of virus from foreign countries, and the amount of air pollution is reduced to a minimum. Thus, the rate of virus transmission could be reduced in Kerala due to reduced transport of air pollutants, substantiating our hypothesis.

4. Practical implications

Our finding that enhanced pollution could offer a direct pathway for airborne transmission of infectious viruses has immediate consequences on preventive mechanisms in the public health medical field. However, the authors caution that there could be several non-linear factors that may potentially affect the rapid transmission of COVID-19, and the present correlation analysis may not fully explain the same. We do take caution in not ascribing all the transmission routes to air pollution alone. Stringent laboratory experiments are required for confirmation of the newly proposed pathway. It calls for the imperative attention of researchers from multidisciplinary fronts to address the problem of environmental influence on rapid transmission of pandemic such as SARS-CoV-2, and urges the authorities to formulate stringent policies that could help curtail enhanced pollutant emissions.

Credit author contributions

M.G. Manoj, designed the study, drafted the manuscript, Satheesh Kumar M.K., designed the study, drafted the manuscript, Valsaraj K.T., provided revisions to the manuscript, and all authors approved the manuscript. Sivan C. did the data analysis, Soumya K. Vijayan, provided interpretations to the findings with key materials,

Declaration of competing interest

None.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.envres.2020.110001.

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