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Understanding air and water borne transmission and survival of coronavirus: Insights and way forward for SARS-CoV-2

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HIGHLIGHTS

• Research insights on interaction of SARS-COV-2 with aerosols and surfaces
• Probable air, water and faecal borne transmission routes of COVID-19 are discussed
• Particulate matter commonly present on surfaces, and surface characteristics can impact virus survival and transmission
• Exploration of effect of confounding environmental factors is needed to better characterize viruses

GRAPHICAL ABSTRACT

ABSTRACT

The ongoing pandemic of coronavirus disease 2019 (COVID-19) caused by the severe acute respiratory syndrome coronavirus 2 (SARS-CoV-2) has resulted in unprecedented disease burden, healthcare costs, and economic impacts worldwide. Despite several measures, SARS-CoV-2 has been extremely impactful due to its extraordinary infection potential mainly through coronavirus-borne saliva respiratory and droplet nuclei of an infected person and its considerable stability on surfaces. Although the disease has affected over 180 countries, its extent and control are significantly different across the globe, making it a strong case for exploration of its behavior and dependence across various environmental pathways and its interactions with the virus. This has spurred efforts to characterize the coronavirus and understand the factors impacting its transmission and survival such as aerosols, air quality, meteorology, chemical compositions and characteristics of particles and surfaces, which are directly or indirectly associated with coronaviruses infection spread. Nonetheless, many peer-reviewed articles have studied these aspects but mostly in isolation; a complete array of coronavirus survival and transmission from an infected individual through air- and water-borne channels and its subsequent interactions with environmental factors, surfaces, particulates and chemicals is not comprehensively explored. Particulate matter (PM) is omnipresent with variable concentrations, structures and composition, while most of the surfaces are also covered by PM of different characteristics. Learning from the earlier coronavirus studies, including SARS and MERS, an attempt has been made to understand the survival of SARS-CoV-2 outside of the host body and discuss the probable air and water-borne transmission routes and its interactions with the outside environment. The present work 1) Helps appreciate the role of PM, its chemical constituents and surface characteristics and 2) Further identifies gaps in this field and suggests possible domains to work upon for better understanding of transmission and survival of this novel coronavirus.

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1. Introduction

Since the COVID-19 outbreak started in late 2019, over 17.5 million people across more than 180 countries have been infected, resulting in more than 680,000 deaths as of early August 2020 (Dong et al., 2020). This is the third and the largest coronavirus outbreak after the severe acute respiratory syndrome coronavirus (SARS)-CoV in 2002–2003 and Middle East respiratory syndrome (MERS)-CoV in 2012 (Xu et al., 2020b).

Cough, fever, and shortness of breath are common symptoms of COVID-19 infection; in severe cases, COVID-19 can cause pneumonia, acute respiratory syndrome, kidney failure, and even death (Huang et al., 2020a; Wang et al., 2020b). The average incubation period of the virus is 3–7 days (median of 5.1 days with 95th percentile of 14 days) (Lauer et al., 2020; Zhu et al., 2020b). Clinical symptoms of critical patients with COVID-19 resembled most of SARS and MERS cases (Wang et al., 2020b). SARS-CoV-2 shares almost 80% of the genome with SARS-CoV and almost all encoded proteins of SARS-CoV-2 are homologous to SARS-CoV proteins (Chan et al., 2020; Xu et al., 2020b).

Hence, the data available on treating SARS may be useful as a reference for COVID-19 treatment (Chen et al., 2020; Morse et al., 2020).

There are interesting studies reported earlier in understanding the behavior of SARS and MERS coronaviruses and the factors and mechanisms influencing its survival and transmission on various air quality and meteorological parameters. SARS, originating in China, had reported 8437 cases and 813 deaths with a fatality rate of almost 10% (WHO, 2004). Studies have found its associations with various factors such as temperature (Tan et al., 2005) and ventilation rates (Cui et al., 2003). The MERS-CoV was first identified in Saudi Arabia in 2012, does not seem to exhibit high interhuman transmission unless there is close contact, but has a high fatality rate of almost 35%; as of January 2020, a total of 2519 cases of Middle East respiratory syndrome (MERS), including 866 associated deaths (Breban et al., 2013; WHO, 2020a). Studies on MERS have also looked into seasonal patterns, visibility, weather conditions, temperature, relative humidity, UV Index, wind speed and indoor air exchange rates (Altamimi and Ahmed, 2020; Gardner et al., 2019; Satheesan et al., 2020). These studies on SARS and MERS outbreaks suggest that pollution and meteorological factors can play an important role in the spread of coronavirus outbreaks, in addition to co-morbidity related impacts of pollution.

This study looks into relevant literature on factors of transmission and survival of the SARS-CoV-2, which include meteorology, air pollution, aerosol droplets size and constituents, wastewater contact, inanimate surfaces, and other chemicals. Chemical composition of these factors is also looked into, which can significantly impact SARS-CoV-2 survival and transmission. Finally, this study outlines probable air and water borne routes and suggest a way forward highlighting the need for investigating the effect of particulate matter characteristics on survival and transmission of SARS-CoV-2 due to the prominent presence of PM in ambient spaces, and on the surfaces.

2. Transmission and survival

Hospitals and quarantine centres (institutional and residential) are high-risk environment for nosocomial transmission; data which included information on whether the patient was a healthcare worker in the United States, reported that 19% were healthcare workers (N = 49,370) (CDCCMMWR, 2020) compared to 20% for MERS and around 21% for SARS (Mackay and Arden, 2015; Wang et al., 2020d). These numbers suggest that extra disinfection and preventive measures, as well as precautions, need to be taken in the healthcare facilities to minimize the cross infection, as the staff spends most of their time in close vicinity of the infected patients.

Outside of the hospital, community transmission can happen through close contact with infected family members or in crowded public spaces (Liu et al., 2020a). Community transmission from an asymptomatic carrier is also a possibility (Al-Tawfiq, 2020; Bai et al., 2020; Gandhi et al., 2020; Huang et al., 2020b; Kaur et al., 2020; Li et al., 2020). Once inhaled, SARS-CoV-2 targets a cell-surface receptor called angiotensin-converting enzyme 2 (ACE2), which is highly expressed in the respiratory tract, lungs, intestine, kidney, and heart; this pathogenesis mechanism is described in detail elsewhere (Docea et al., 2020; Torequl Islam et al., 2020; Yuki et al., 2020). Common modes of transmission are outlined below.

2.1. Droplet transmission

Transmission through saliva droplets has been a common and most effective transmission mechanism considered. Exhalation (via sneezing or coughing) from the infected patients are in the form of respiratory droplets (diameter > 5–10 μm) and droplet nuclei (diameter < 5 μm) (WHO, 2020b). Respiratory droplet transmission can occur at a distance of up to 1 m, whereas airborne transmission of virus-laden droplet nuclei exhaled by an infected person, which are small enough to remain airborne can travel over distances greater than 1 m (WHO, 2020b) and potentially even up to of tens of meters in the air (Morawska et al., 2009; Morawska and Cao, 2020). There is a substantially probability of transmission of COVID-19 through speech droplets, in addition to sneezing and coughing (Stadnytskyi et al., 2020). Respiratory droplets can also undergo evaporation and transform into droplet nuclei (Wells, 1934). Austin, the virus-laden aerosols can interact with various components of the atmosphere, which can affect its survival. If exposed to a toxic component of the atmosphere, it may get inactivated and no longer transmit the disease, alternatively exposure to a benign component survive for longer period and may or may not transmit the disease depending on the residence time. Atmospheric interactions have been discussed in Section 3.

Half-lives of SARS-CoV and SARS-CoV-2 in aerosols are similar and reported to be approximately 1.1 to 1.2 h (van Doremalen et al., 2020). It is easy to understand that this transmission mechanism will be among the most important reasons for disease spread making its containment a very difficult task and necessitating the need for social distancing.

2.2. Contact or fomite transmission

Respiratory droplets exhaled from an infected person settle down on nearby fomites, enabling another common route of infection, especially through community spread (Kampf, 2020). In the case of fomite transmission, a person’s hand or body part may come in contact with the infected surface and eventually enter the body through the nose or mouth. Reported median half-life of SARS-CoV-2 is approximately 5.6 and 6.8 h on stainless steel and plastic respectively; no infectious SARS-CoV-2 was measured on copper and cardboard after 4 h and 24 respectively (8 h each for SARS-CoV) (van Doremalen et al., 2020). SARS-CoV-2 can survive on inanimate surfaces such as printing papers and tissue papers for up to 3 h, treated-wood for up to 2 days; can last longer on smoother surfaces such as glass and banknotes for up to 4 days, and stainless steel and plastic for up to 7 days. Interestingly the virus was detected even after seven days on the outer layer of a surgical mask (Chin et al., 2020). The survival of SARS-CoV-2 on surfaces is summarized in Fig. 1. Therefore, fomite transmission would depend on the surface characteristics, which can affect virus survival and can help determine extent of spread of the disease. However, it is not justifiable to consider that these surfaces will always be free from dust and particles, which can have significant impacts on virus survival in addition to inherent surface properties as often studied. These interactions have been explored in Section 5.

2.3. Faecal transmission

The third mode of probable transmission of coronaviruses is via faeces. A controlled study on aerosolization of faecal waste contaminated with avian influenza virus shows that faecal transmission could be a
serious risk for both humans and animals (Sedlmaier et al., 2009). In an earlier study, SARS-CoV is reported to be stable in faeces at room temperature for a minimum of 1–2 days and can survive for up to 4 days in stool from diarrheal patients (Lai et al., 2005). SARS-CoV-2 is also detected in faeces raising the possibility of faecal-oral transmission (Liu et al., 2020b; Wang et al., 2020c; Yeo et al., 2020); especially during flushing which can aerosolize faecal matter, resulting in airborne transmission (Section 2.1) (McDermott et al., 2020). Such probability of transmission is high in hospital and quarantine centers settings where toilets are shared.

Flushed water entering into sewerage systems also becomes another carrier medium for this virus. A previous study determined that coronaviruses can survive up to 2–3 days in sewage water and up to 10 days in tap water at 23 °C; factors for survival include temperature, organic matter levels and presence of antagonistic bacteria and oxidants such as chlorine (Gundy et al., 2009). These aspects of aerosolization through flushing and entry into sewage calls for detailed analysis and focused research in this area. Such type of probable routes of transmissions should be thoroughly researched for virus transmission and survival in these mediums as these possibilities may aggravate the problem to community transmissions (Heller et al., 2020). Some of the early researches in this area has suggested presence of RNA of SARS-CoV-2 in sewage water (Gu et al., 2020; Xu et al., 2020a), however, the persistence of the virus in water and sewage is yet to be determined (La Rosa et al., 2020). The chemical components of faecal matter are mostly organic in nature and can promote the extended survival of the virus in this phase (Fig. 1). Further, poor sanitation conditions and practices such as open defecation (which is commonly observed in rural areas or less-developed countries), coupled with unhygienic practices can potentially result in transmission via fomites as well (Section 2.2).

### 3. Interactions of virus-laden nuclei with particulate matter and environmental factors

The research studies have highlighted that the air-borne transmission of coronavirus is one of the most potential ways of its infection (Morawska and Cao, 2020; Setti et al., 2020). The studies have also suggested that inhalations of virus laden droplet nuclei can possibly infect an individual in direct contact, however the droplet nuclei (diameter < 5 μm) can become air-borne and travel greater distances compared to respiratory droplets (diameter > 5–10 μm), thereby increasing the zone of spread. Ultrafine particles present in ambient air have residence times in the order of days or weeks enabling transport up to thousands of kilometers in the atmosphere, while coarser particles, which are heavier tend to deposit quicker and typically travel less than 10 km from their place of generation. (WHO, 2006), although the extent of transport of virus-laden particles needs to be explored. While there is a lack of concrete evidence of long-distance aerial transmission of coronavirus infections, studies suggest that PM can act as a potential carrier for the viral droplet nuclei, eventually spreading the virus and other pathogens (Sanità di Toppi et al., 2020). These airborne virus laden droplet nuclei can also then interact with particulate matter, by getting adsorbed on the particulate surfaces, can further travel in the atmosphere increasing damage (infections) distances.

Although the PM can play a role in harboring microorganisms including coronavirus, the interaction of varied composition of the PM with coronavirus remains unaddressed i.e. transmission and survival of virus on PM with different constituents/compositions, including black carbon and heavy metal particulates etc. On the other hand, exposure to PM levels exceeding the guidelines (for yearly average PM2.5 and PM10 exposure is 10 μg/m3 and 20 μg/m3 respectively) and can adversely affect the immune system (WHO, 2006) thus further aggravating not only infection potential of virus but also severity of health impacts. There is substantial evidence of both short-term and chronic exposure to high levels of fine- ultrafine PM and other anthropogenic pollutants being associated with detrimental health effects including exacerbating pre-existing respiratory diseases, by deposited deep inside the lungs, especially pulmonary alveoli (Chen et al., 2016), through a combination of inertial impaction, gravitational sedimentation, and diffusion mechanisms (Darquenne, 2014). Inhaled PM2.5 can get deposited in different compartments in the respiratory tract and interact with epithelial cells and resident immune cells, inducing local or systemic inflammatory responses (Wei and Tang, 2018). Thus, if the particulates are virus laden, the exposure may worsen the health condition of an individual, by not only infecting a person with COVID-19 but also could also impact the individual immune system, thereby increasing the viral infectivity, morbidity and mortality, especially in children and adults (Pope III, 2007; Li et al., 2016; Pope et al., 2018; Kinnane et al., 2019; Tsatsakis et al., 2020).

Apart from air-borne inhalations of the virus and PM, these interactions could also frequently happen on the different environmental surfaces, where the coarse PM and virus-laden respiratory nuclei can
settle and contaminate surfaces. Along with the PM, atmospheric bioaerosols including viruses, fungi, bacteria, and algae, whose combination with PM, could be associated with improved virus survivability, possibly promoting the ability of the virus to grow and multiply (Turaga et al., 2012). Increased abundance of microbes have been reported during high PM pollution and smog events as compared to clear and sunny days (Cao et al., 2014; Wei et al., 2016). Now, when such infected surfaces are touched, can act as a path to introduce the virus to an individual by mouth, nose, or eyes. These surfaces can also re-suspend in the virus-laden particulates during high wind turbulence, simultaneously enabling air-borne infections.

It is also critically essential to investigate and to understand the impact of PM compositional characteristics and morphology on virus survival, which will prominently determine its spread from air and surfaces, as many compounds associated with PM can be toxic to the virus survivability. As a first step, highlighting the need, the presence of heavy metal particulate matter and its interaction with the virus is discussed in subsequent Section 4.1. It can be inferred that different PM compositions can have different survivability of the virus and thus, the role of PM aiding the air-borne and surface transmission can’t be generalized and present an important subject for further study.

There has been a substantial number of recent studies characterizing SARS-COV-2 and its association with criteria pollutants and environmental parameters. Table 1 summarizes outcomes of selected recent studies, which looked into associations of some of these factors with COVID-19 transmission and mortality.

From Table 1, it could be inferred that higher temperature, UV radiation and wind speeds are associated with lower risk of COVID-19 transmission, although other political/administrative, demographic, environmental and scientific factors will have confounding effects (Bherwani et al., 2020a, 2020c; Goumenou et al., 2020). The effect of humidity on the virus transmission, is not clearly understood and would require more scientific evidence to establish the cause and effect relationships. It is also reported that the effect of environmental factors, will be greatly undermined, the social (physical) distancing is not properly followed (Bherwani et al., 2020b; Gupta et al., 2020).

Studies looking into both short- and long-term exposure to criteria pollutants found confirmed associations of pollution levels with COVID-19 spread or fatalities, with higher levels resulting in increased fatalities. This could be mainly due to the health impacts of such pollutants, which would make the people more vulnerable to COVID-19 infection and may not be actually considering the stability of the virus on polluted surfaces, especially with respect to PM composition. Interestingly, short-term exposure to a higher concentrations of SO2 is associated with decreased risk of COVID-19 infection (Zhu et al., 2020a), thereby further strengthening and testifying the present hypothesis that atmospheric chemistry and PM characteristics can significantly affect virus survival as this can play a vital role in the spread of disease through both most potential modes of transmissions, i.e. airborne and fomite.

### 4. Interaction with other chemicals

Studies on virus survival and interaction with different surfaces and chemicals have also been reported in an effort to better understand SARS-CoV-2 survival characteristics.

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**Table 1**

Summary of COVID-19 studies on different environmental parameters and pollutants and their outcomes:

| Study location and details | Parameters explored | Major Outcome | Reference Authors, Year |
|----------------------------|---------------------|---------------|-------------------------|
| 122 cities in China        | Daily mean temperature, RH, air pressure, and wind speed. | Approximately linear relationship between mean temperature and COVID-19 confirmed cases was in the range of <3 °C. Increasing ambient daily average temperature up to around 13 °C negatively associated with daily cases of COVID-19. | Xie and Zhu (2020) |
| 31 provinces in Mainland China | Ambient daily average temperature | Effective reproductive number (R) is reduced for both China and USA with increase in temperature and RH. | Oliveira et al. (2020) |
| 100 Chinese cities and 1005 US counties | Temperature and RH | Cities with more than 100 days of exceedance of PM10 or O3 guidelines exhibit higher infections. Low wind speed, high moisture and occurrences of foggy days associated with increased transmission. | Wang et al. (2020a) |
| 55 Italian province capitals | PM10, O3 and Wind data from 2018 | | Coccia (2020) |
| Jakarta, Indonesia | Minimum temperature, maximum temperature, average temperature, humidity and rainfall | Only average temperature was significantly correlated with the COVID-19 pandemic. | Toepu et al. (2020) |
| Chinese Provinces | Temperature and humidity | 1 °C (above 5 degrees) increase results in a 10% decrease in the spread of the virus. Very little probability of there being any relationship between humidity and infectiousness. | Gupta (2020) |
| 2 Indian states and 3 Indian cities with 1 city in US as Control Case. | Temperature and Relative Humidity | Effect of temperature is greatly undermined by social distancing factor. Effect of humidity is not conclusive. The overall impact of temperature and humidity gets confounded with other environmental factors like air pollution etc. | Bherwani et al., (2020b) |
| All 50 US states and Washington DC | Average Humidity | Significant positive correlation between humidity and COVID-19 mortality | Li (2020) |
| 0.25 × 0.25° grid across China | Temperature, specific humidity, UV radiation (satellite derived) | Temperature (0–10 °C), specific humidity (2–6 g/kg), and UV-B radiation (< 1.5 MJ m–2 d) within the specified range may contribute to higher transmission risks for COVID-19. | Wen et al. (2020) |
| 30 Provincial capitals of China | Ambient temperature, diurnal temperature range, absolute humidity, migration scale index | Low temperature, mild diurnal temperature range and low humidity likely favor COVID-19 transmission. | Liu et al. (2020c) |
| USA (County-level) | Satellite derived PM2.5 (adjusted for 20 potential confounding factors) | Increase of 1 μg/m³ in PM2.5 associated with an 8% increase in the COVID-19 death rate. Both temperature and relative humidity negatively related to the daily cases and deaths of COVID-19. COVID-19 pandemic may be partially suppressed with temperature and humidity increases. | Wu et al. (2020b) |
| 166 countries | Temperature and humidity | | Wu et al. (2020a) |
| 120 cities in China | Criteria pollutants: PM2.5, PM10, SO2, CO, NO2, and O3 association with daily confirmed cases | Short-term exposure to all criteria pollutants except SO2 associated with increased risk of infection. | Zhu et al. (2020a) |
| Northern Italy and Central Spain | Satellite derived NO2 and dispersion modeling | Long term exposure to NO2 can lead to higher fatality rates of COVID-19. | Ogen (2020) |
| 9 Asian cities in China, India, Pakistan and Indonesia | PM2.5 and PM10 | High PM2.5 exposure over a long period (10 years) found to significantly correlate with present COVID-19 mortality per unit reported cases. PM10 exposure did not exhibit significant correlation. | Gupta et al. (2020) |
4.1. Metal ions

Metal ions play an important role in the survival of viruses. Mg, Zn, and Cu are some of the metal ions that can bind to virus proteins and can be part of RNA and DNA processes (Tunde et al., 2020). Derivatives of bismuth have shown to efficiently inhibit the growth of SARS-CoV (Yang et al., 2007). Zinc derivatives have been proven to work against influenza, poliovirus and SARS-CoV in cell cultures (te Velthuis et al., 2010). Zn$^{2+}$ has also shown to inhibit coronaviruses (Tunde et al., 2020). A comprehensive review of the role of heavy metal complexes such as Ni, Mg, Co, Fe, Cu and their interactions with different viruses is reported by Tunde et al., 2020. Metal ions can be deposited on surfaces and interact with the virus; further research on the exploration of their effect on virus survival is suggested.

4.2. Essential oils

Antiviral properties of essential oils and their components have been well documented and studies have demonstrated substantial inhibition of different strains of the influenza virus, dengue virus, and others (Nerio et al., 2010; Raut and Karuppayil, 2014). More recently, a study showed that organosulfur compounds which are major components (>99%) of garlic essential oil, have strong interactions with SARS-CoV-2 suggesting that this food ingredient is a valuable natural antiviral source and contributes in the prevention of invasion of the virus into the human body (Thuy et al., 2020). Additionally, organosulfur compounds like quercetin and allicin are associated with inhibition of viral infection (Sharma, 2019). These observations suggest that natural sources of organosulfur compounds such as garlic, onion, cooked meat, fish and leeks can play an active role in inhibiting coronaviruses; however, higher doses cause toxicity and health effects depending on the biological environment (Sahu, 2002). Essential oils can be both present on surfaces and undergo aerosolization. A summary and review of the antiviral properties of essential oils is recently reported by da Silva et al. (2020).

Organosulfur compounds that have proven to show inhibitory properties against SARS-CoV-2 and other pathogens come under a larger family of chemicals known as phytochemicals, which are chemical compounds produced by plants. A wide variety of active phytochemicals have been found to have therapeutic applications against a variety of viruses (Chandel et al., 2020) and are listed in Fig. 1. Mani et al. (2020) also identified key phytochemical compounds that have the potential to treat COVID-19 such as scutellarein, silvestrol, tryptanthrin, saikosaponin B2, lectins such as grifolin, lycorine and polyphenolics – including quercetin, myricetin, caffeic acid, psoralidin and isobavachalcone. The exploration of drugs and remedies based on phytochemicals is warranted.

4.3. Disinfectants

Disinfectants, although not naturally produced, are the most effective and short-term solution to eliminate viruses and other pathogens. The United States Environmental Protection Agency (US EPA) has outlined viable disinfectants for SARS-CoV-2, active ingredients of which include ethanol, isopropanol, hydrogen peroxide, citric acid, glycolic acid, lactic acid, octanoic acid, peroxyacetic acid, phenolic, quaternary ammonium, chlorine dioxide, hydrochloric acid, hypochlorous acid, sodium chloride, sodium dichloroisocyanurate, sodium hypochlorite and thymol (Fig. 1). Their range of use can include various surfaces including clothes, food, glass and other surfaces (US EPA, 2020) and aerosolization is also a possible mechanism.

Depending on the dilution and the chemical nature of the active ingredient, the timeframe of virus disinfection can vary between a few seconds to 30 min, although most of the commercially available disinfectants take 10 min or less (US EPA, 2020). However, caution is required as they can damage the surfaces, and skin contact or ingestion of these chemicals can be detrimental to human health.

5. Discussion and future prospects

Drawing on above discussion, there are many studies on SARS-CoV-2 and similar viruses from which knowledge could be straining to understand its nature in terms of survival and transmission. However, it could be noticed that most of the studies are related to the impact of various compounds and surfaces on the survival of coronaviruses. However, the role of PM especially considering its chemical compositions, morphology, particle size coupled with its frequent presence of almost all the surfaces can be very relevant in the air, water andomite borne transmissions of such pathogens. Studies looking into virus survival on common surfaces have been generally done under controlled laboratory settings and more importantly on clean surface for obvious reasons. For instance, the work by van Doremalen et al. (2020) when looking into surface stability of SARS-CoV-2 maintained the surfaces at a constant temperature (21–23 °C) and specified relative humidity for 7 days. It is also likely that the surfaces were not contaminated with external particulate matter during the experiments to achieve reproducible results and to study specific surface characteristics. While these observations are vital in characterizing pathogens, such studies should be extended to account for the dynamic variability associated with the real-world environment and micro-environment including the effect of environmental and other external factors. In reality, PM is always omnipresent and deposition of PM on surfaces in various forms and states is a common phenomenon that cannot be overlooked. Surface deposition can be categorized as: 1) Particles (dust, metals, ceramics, glass, plastics etc.), 2) Thin-film or molecular contamination (organic or inorganic), 3) Ionic contamination (Na$^{+}$, K$^{+}$, Cl$^{-}$, F$^{-}$, SO$_{3}^{2-}$, BO$_{3}^{3-}$ and PO$_{4}^{3-}$), 4) Metallic contaminants in the form of discrete particles or trace impurities and, 5) Microbial contamination (Kohli and Mittal, 2018).

Hence, PM plays a multifaceted role of providing surfaces for pathogen transmission and interaction, enabling fomite transmission by deposition, as well as chronic weakening of the immune and respiratory system, making the virus more potent in regions with higher PM levels. Its omnipresence in the atmosphere and on surfaces (due to deposition), makes it an important subject for further study to understand the impact of PM composition on virus survival, which will prominently determine its spread from surfaces rather than the only type of surfaces as studied so far.

Further, the chemical composition and mass concentrations of PM is highly variable and dependent on local geography, meteorology, seasonal patterns and sources of emissions such as traffic, re-suspended dust, industrial, residential, biomass burning, natural and other sources (Karagulan et al., 2015). SARS-CoV-2 (diameter 60–140 nm) can attach itself to PM components such as dust or marine organic aggregates and eventually deposit (Sanità di Toppo et al., 2020). Some of the constituents of PM which may interact with these viruses are compiled in Table 2.

| PM Component | Description |
|--------------|-------------|
| Size $<$0.7 μm | Implying longer residence time and further dispersion of viruses (Reche et al., 2018) |

Virus deposition rates are positively correlated with organic aerosols of size $<$0.7 μm, implying longer residence time and further dispersion of viruses (Reche et al., 2018). Hence PM can play a vital part in virus transmission and survival. Nature of the role played by PM should be thoroughly examined so as to understand its efficacy in aiding or reducing the transmission and survival of these viruses. Further, PM also exhibits varied morphological characteristics by location and source, which are very likely to also exhibit different virus responses.

Particulate matter, being a complex mixture, having variable physicochemical properties can have a mixed impact on virus survival ranging from extended survival (such as aerosolized faecal matter), benign (where it simply acts as an inanimate surface until inactivation) to toxic. It is of immense importance to extend such studies and understanding of inhibitory or otherwise properties of common pollutants including PM constituents comprising of a range of PAH, other organic compounds as well as the morphology of the fine particles, which have mostly not been studied so far. Further research is warranted on virus survival on major individual components of PM to develop a better understanding of the role of PM.
This lack of above information prevents complete understanding on the stability of coronavirus on PM and PM-contaminated common surfaces. These particles are almost omnipresent and can significantly influence the interaction of viruses with different surfaces studied so far, as often these surfaces are not completely clean in real world conditions. This certainly presents a very complex matrix to be explored, however considering its presence in spaces and atmosphere, such investigations will be of great significance to improve knowledgebase on understanding the behaviors of different viruses/ microorganisms, which eventually determines their infection potential through spread as well as their mutations. Moreover, given the depth of existing research and knowledge, it is high time that the effect of confounding factors such as variation in temperature, humidity, composition of PM and so on, should be explored in detail to understand the chances of real-life survivability and transmissibility of viruses such as SARS-CoV-2.

Fig. 2 summarizes the discussion related to PM in the context of virus infection. Exhaled respiratory droplets, which are relatively heavier will deposit and contaminate nearby surfaces and spread to other individuals via fomite transmission until the virus loses its infectivity either by natural decay or chemical decontamination. Exhaled droplet nuclei, once airborne, can be inhaled by other nearby individuals but not before undergoing exposure to environmental factors such as temperature, relative humidity and wind speed/ventilation, along with the various physico-chemical interactions with other components in the atmosphere including PM, which can further affect virus transmission and survival and even inactivation of the virus. For instance, the presence of SO2, volatile organic compounds (VOC’s) emitted from essential oil volatilization and/or aerosolized disinfectants could hypothetically inhibit or kill, although further studies on the individual effects of such components is warranted. Flushing related aerosolization of virus laden particles will likely undergo similar fate. Hence, evidently, there are enough and important reasons to explore interactions of environmental factors and constituents of PM to fill the gaps identified in this work.

CRediT authorship contribution statement

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Declaration of competing interest

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

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