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The COVID-19 pandemic: Virus transmission and risk assessment
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Abstract
The coronaviruses are the largest known RNA viruses of which SASR-CoV-2 has been spreading continuously due to its repeated mutation triggered by several environmental factors. Multiple human interventions and lessons learned from the SARS 2002 outbreak helped reduce its spread considerably, and thus, the virus was contained but the emerging mutations burdened the medical facility leading to many deaths in the world. As per the world health organization (WHO) droplet mode transmission is the most common mode of SASR-CoV-2 transmission to which environmental factors including temperature and humidity play a major role. This article highlights the responsibility of environmental causes that would affect the distribution and fate of the virus. Recent development in the risk assessment models is also covered in this article.

Introduction
Coronaviruses, in general, were known to be of veterinary impact only until the severe acute respiratory syndrome (SARS) outbreak in 2002 [1]. Among the various genera of coronaviruses, members of both alpha and beta coronaviruses have been proven to infect humans. Before the SARS outbreak, 19 coronaviruses were identified, including 15 mammalians (2 infecting humans) and 4 avian coronaviruses [2]. Similarly, 5 other human coronaviruses (HCoV) currently in circulation in the human population include the alpha coronaviruses, HCoV-NL63 and HCoV-229E and betacoronaviruses, HCoV-OC43 and HKU1 [3]. The enveloped viruses have a similar structure, that is, a lipo-proteinaceous, host-derived envelope covering a nucleocapsid formed of viral protein strings that finally encloses the virus’s genetic material with or without specific regulatory proteins (Figure 1) [22,52]. Human immunodeficiency virus (HIV) [4], Ebola, dengue, Zika, and coronaviruses are examples of some enveloped viruses that have been the cause of major viral outbreaks in the past and are zoonotic [5–7]. Thus, when the source of SARS coronavirus-2 (SARS-CoV-2) is unclear, the rapid transmission of this virus could be explained with the help of several environmental factors which govern transmission and establishment of the infection. Moreover, the severity of an outbreak depends not only on the lethality of the virus but also upon its mode of transmission and the availability of cure/vaccine [8]. Vaccination and disease management has been able to control diseases like polio and HIV-acquired immunodeficiency syndrome (AIDS), respectively, but the novel SARS-CoV-2 is continued to be a global pandemic even when mass vaccination is at its peak in several parts of the world. Understanding the factors that work in favour and/or against the SARS CoV-2 will help predict and prepare for future outbreaks. While governments and scientists are pondering over the possibility of reinfec- tion, modes of transport of the virus and nature of the dormant stage, the part of the environment in the spread of the disease and subsequent risk assessment are of paramount importance. The article is divided into four major sections. A virus transmission follows the introduction, and the role of temperature and humidity is discussed in Section Virus transmission. Section Risk assessment highlights the recent developments on risk assessment strategy to combat the transmission. Research gaps and precautionary measures are highlighted in the conclusion section.

Virus transmission
The structural and genetic differences between the viruses allow them to infect various hosts and make them
vulnerable to different environmental stress. Several factors, including air temperature [9,10], size of the aerosol droplet [6,10] and relative humidity [10,11], the stage of infection in the index person [12] would determine the transmissibility of the virus through air. For instance, asymptomatic patients infected with SARS-CoV who travelled in an aircraft did not affect any onboard passengers, although other environmental factors were conducive to disease transmission [13,14]. During the incubation time of the virus within a human host, the host exhibits no symptoms. Hence, chances of coughing or sneezing remain low, and correspondingly, the chances of transmission are also low. However, such conclusions do not hold for the transmission of SARS-CoV-2 as transmission from asymptomatic patients is also well documented [15,16]. The transmissibility and reproduction number (R0) of SARS-CoV-2, that is, 3.28 with a median of 2.79 is greater than that of SARS-CoV infections in Singapore, and Hong Kong where R0 was estimated to be 2.7 and 2.1, respectively [17,18]. Another article also reported slightly high value for SARS-CoV-2 R0, that is, 5.7 [19]. Such instances indicate alternative transmission routes and may be attributed to genetic and molecular variations between SARS-CoV and SARS-CoV-2. The two extremely crucial elements that can affect viral survival and viability in droplets are relative humidity and temperature.

Role of relative humidity (RH)
At low RH, the droplets evaporate rapidly. The lower the RH, the smaller is the final droplet size [20]. This leads to the retention and concentration of viral particles in a smaller droplet, travelling longer distances than larger droplets. Some studies report that SARS-CoV-2 can transmit at a higher rate in dry and indoor places of low humidity (< 40%) than that of high humid places (i.e., >90% RH) [21]. Additionally, under such conditions, along with the virus, several salts and proteins may also be trapped within the droplet [20]. Evaporation alters the microenvironment of the droplet significantly, and many viruses and other microbes may be inactivated due to the increased salinity (from mucous or saliva) within the droplet [20]. However, enveloped viruses, which are usually hydrophobic, are reported to be surrounded by hydrophobic moieties and proteins, making their inactivation within the droplet extremely difficult.

Previously, studies with the human coronavirus 229E and SARS-CoV demonstrated that the viruses were stable for up to 6 days at a relative humidity of 50% (Geller et al., 2012). The case study pertaining to transmission of infection from one symptomatic passenger travelling in an aircraft to 18% of the healthy travellers onboard during the SARS-CoV outbreak [13] established the transmissibility of coronaviruses through the air at low humidity. Low humidity coupled with air re-circulation systems were proposed as the reasons for the spread. A retrospective sketch of the seating pattern in the aircraft indicated that the spread was mediated via small droplets or aerosols. The larger, more visible droplets could only travel ~36 in, which was less than the distance between the seats in the aircraft. Even seating within two rows from the index person could increase the risk [12].

The genome organisation of SARS-CoV-2 with specific amino acid insertions present in S protein. (a) Gene organisation of SARS-CoV-2. (b) Sequence comparison of amino acid residues of RBD of the S protein of closely related CoVs. The residues in red are the conserved residues present in all the sequences compared. The residues highlighted in green are mutations in the current SARS-CoV-2. (c) Polybasic furin cleavage site (RRAR) present in SARS-CoV-2 not in other closely related CoVs. The presence of such polybasic cleavage sites in other viruses have been shown to be a determinant of pathogenicity.
Higher viability of SARS-CoV-2 at lower relative humidity may also explain why the pandemic started when winter gave way to spring, that is, when most of China, Europe, and the USA had lower relative humidity than during the summer months. Another interpretation of this transmission mechanism was suggested by Sun et al. (2020) [23]. During periods of decreased RH, the mucosal layer may not trap pathogens as effectively as during higher RH, enabling increased chances of infections during this time at an infectious dose if present in the air. Contradictorily, Gunthe et al. (2020) described no major correlation between RH and the number of persons infected in 80 locations worldwide [24]. Similarly, no statistically significant correlation was reported when RH (>70%) values from 127 countries were used to study the variation in daily COVID-19 cases [25]. Another study reported that droplets could travel much further in a high-humidity environment. But, the generation of aerosol particles increases in low-humidity environments, which remain suspended in the air for several minutes to hours [10], facilitating virus transmission (Figure 2). Using the chemistry fundamentals, a mechanistic model found that SARS-CoV-2 inactivation followed a U-shaped dependence on RH [26]. Thus, relative humidity between 40 and 60% is recommended as optimal for human health in indoor places [21].

**Role of temperature**

When researchers studied the effects of temperature on the transmission of the virus using weather data over the period from 23rd January to 10th February 2020 in several countries, including China, Thailand, Singapore, Japan, South Korea, and Taiwan, no decline in transmission of the virus was observed with the increase in temperature and humidity in the Northern Hemisphere [27]. However, a recent article taking into account temperature and UV index data from 85 different locations at different latitudes from 2nd February 2020 to 10th March 2020 indicated that the SARS-CoV-2 virus was most viable within a narrow temperature range of 5–15 °C and the infection rates were much lower both above and below this range [24]. These results agreed with results

![Figure 2](https://example.com/figure2.png)

**Figure 2**

RH and temperature effect on COVID-19 transmission through droplet contact and exposure to aerosol particles: (a) Effect on maximum droplet spreading distance, (b) aerosolization rate of respiratory droplets, (c) average aerosol particle diameter and (d) total mass of PM2.5 particles [10]. (a) “This figure is made available via the ACS COVID-19 subset for unrestricted RESEARCH re-use and analyses in any form or by any means with acknowledgement of the original source. These permissions are granted for the duration of the World Health Organization (WHO) declaration of COVID-19 as a global pandemic.”
presented by J. Liu et al., (2020), who suggested a low temperature (0–10 °C) with mild diurnal temperature variation (a difference of 4–8 °C) favours disease transmission [28]. Another study on the spread of respiratory droplets and aerosol particles generated by speech under a range of temperatures (0–40 °C) further confirmed that droplets could travel three times farther in low temperature, but more aerosols are generated in high temperature (Figure 2) [10]. At low temperature, the virus can survive the longest with an estimated half-life > 24 h at 10 °C (40% RH) but ~1.5 h at 27 °C (65% RH) [26]. The time required to decrease SARS-CoV-2 infection by 90% range from 4.8 min at 40 °C (20% RH) under high intensity simulated sunlight representative of noon on a clear day in the summer indicated the importance of temperature and RH on the virus survival in aerosols and subsequent transmission [29].

Table 1
Environmental factors considered to model SARS-CoV-2 transmission.

| Country or Region | Factors considered                                                                 | Methodology                                          | Key conclusions                                                                 | References |
|-------------------|-----------------------------------------------------------------------------------|------------------------------------------------------|---------------------------------------------------------------------------------|------------|
| United States     | Temperature, humidity, ultraviolet (UV) radiation, and population density         | Regression analysis                                   | Autumn and winter are more vulnerable to increased transmission than the summer season due to low-ambient temperature. | [47]       |
|                   |                                    | Semi-mechanistic epidemiological model               |                                                                                  |            |
| United States     | Air temperature, specific humidity (SH), and UV radiation                          | A dynamic metapopulation model fed by human mobility data was used to estimate \( R_0 \) | Cold and dry weather with low levels of UV rays is fairly correlated with increased SARS-CoV-2 transmission. | [48]       |
|                   |                                    | Exposure–response curves were used to study the association | Further, the leading factor, that is, SH of low levels, significantly correlated with the increased SARS-CoV-2 transmission. |            |
| China             | Temperature, humidity, ventilation, hygiene facility                             | On-site simulations were conducted with a variable air temperature (19–20 °C) and RH (55.5%) | Low temperature and high RH, poor ventilation, and insufficient hygiene facilities may contribute to viral transmission | [49]       |
| 26 countries across the globe | Temperature, absolute humidity (AH), RH, solar surface radiation, wind speed, precipitation and \( R_0 \) | Multilevel meta-regression model                      | AH has a strong indoor-to-outdoor correlation, indicating that outdoor AH measures could reflect indoor conditions. | [50]       |
|                   |                                    |                                                      | However, there is a poor association of weather parameters with COVID-19 transmission. |            |
| China             | RH (%), temperature (mean, minimum and maximum), sunshine hours, wind speed, and rainfall | Standard time-series approach and then the region-specific regression analysis | Meteorological factors play mixed positions in virus transmission, and seasonality has a key role. | [51]       |
| United States     | Droplet velocity, RH, temperature, distribution of initial droplet size, and background air velocity | Modelling was done to predict critical distance and aerosolisation rate for speech droplets in various environmental conditions. | Droplets can move 3 times beyond in low-temperature and high-AH conditions. | [10]       |
|                   |                                    |                                                      | High number of aerosols are generated at high-temperature and low-AH condition. |            |
| –                 | Aerosol concentrations, viral load, infectivity rate, viral viability, lung-deposition probability, and inhalation rate | CFD model was used to study aerosol transport on a spatial and temporal scale | Social distancing could significantly decrease the aggregate exposure by two factors allowing enough time for dilution and dispersion | [43]       |
| China             | Ventilation air distribution                                                    | Tracer gas experiments                                      | Infection dispersal is steady with the spread pattern of long-range transmission of respired virus-laden aerosols. | [46]       |
|                   |                                    | CFD simulations                                          | SARS-CoV-2 transmission is feasible in packed places with a ventilation rate of 1 L/s per person. |            |
Recently, many studies considering several environmental factors including RH, temperature, UV radiation, population density, ventilation, wind speed, precipitation, aerosol concentration and air distribution to model the SARS-CoV-2 transmission and subsequent modelling as highlighted in Table 1.

Risk assessment
Mathematical modelling plays a starring role in emergency and preparedness design, risk assessment, policy, and decision-making during disease outbreaks. The application of mathematical modelling to SARS [30], influenza [31], West Nile virus [32] and Zika virus [33] is well documented in the literature. By combining genomic and geographical data, Dellicour et al. (2016) studied the mode and tempo of pathogen dispersal during epidemics. Similar attempts were made by Myer et al. (2017) by combining 40 ecological, meteorological, and built-environment covariates, such as precipitation, temperature, septic tanks, sand and soil. Multivariate logistic regression analysis emphasised the role of eight environmental factors (bodies of water, wetlands, transportation routes, migration routes, main cities, precipitation, elevation and poultry density) towards the transmission of avian influenza caused by H5N1 [36]. Integration of the geographic information system (GIS) and binary response models highlighted the significance of small-scale conventional sewage treatment plants and commercial areas favouring norovirus outbreaks [37]. The role of zoonotic reservoirs and spatiotemporal climate variability was also documented in some studies [38,39]. A Bayesian phylogeographic study suggested a significant role of high human density, freight transportation, and temperature on avian influenza virus (AIV) [31]. Hence, by using spatial models which take into account the geographical behaviour of hosts, movement (migration and mixing patterns), and metapopulation models that look at the spread of the diseases at the subpopulation level, risk assessment of the corona outbreak can be made.

A recent review on the factors contributing to the SARS-CoV-2 virus outbreak in Wuhan, China argued that the combination of several factors such as external environment, natural hosts, intermediate hosts and susceptible populations had resulted in the incidence of SARS-CoV in the past, and these could have likewise been responsible for the current incidence of SARS-CoV-2 [23]. The likelihood of the unnatural origin of SARS-CoV-2 cannot be ignored, as has been reported for MERS-CoV using the Grunow—Finke assessment tool (GFT) [40]. However, additional studies may be conducted to support such claims. Integration of Bayesian “Quantitative Microbial Risk Assessment (QMRA)” approach and atmospheric dispersion models, which considers historical wind speed, may allow an assessment of the SARS-CoV-2 infection risk and potential spread, as has been assessed for norovirus infection risk at WWTPs [41]. A detailed review on the pragmatic approach of risk perception to the previously reported spread of diseases, such as SARS and avian influenza, was published in 2009 [42]. While referring to these studies, computational fluid dynamics (CFD) attempts were further made to study the spatial—temporal aerosol concentrations and quantify exposure risk to SARS-CoV-2 considering separation distance, exposure duration, and environmental conditions such as airflow and ventilation and, most importantly, face-covering [43]. However, while performing risk assessment, it is essential to consider the uncertainties around SARS-CoV-2 genome copies deposited in the respiratory tract [44], proximity, that is, interpersonal distance [45], and ventilation facility and air distribution [46], as evaluated for the virus elsewhere.

Conclusions
Epidemic outbreaks following SARS in 2002 and MERS in 2012, and the COVID-19 pandemic have revealed the rapid mutation rates, leading to species breaching and/or wide host range infections. These zoonotic viruses bear envelopes derived from the host cell membrane and thus also bear different envelope proteins. These single-stranded RNA viruses can adapt to rapidly changing ecological niches due to their high substitution rate. This enhances their potential to cause a pandemic, as can be seen, today. Although many theories and correlations were reported to evaluate the role of environmental factors or climatic conditions to study the role of geographical locations using weather data over the period in several countries, no decline in transmission of the virus was observed with the increase in temperature and humidity in the North Hemisphere. However, SARS-CoV-2 is most viable in the narrow temperature range of 5–15 °C and most transmissible at low RH (≤40%). All these factors should be taken into account while performing SARS-CoV-2 transmission modelling. Professionals from various backgrounds must come together and predict diseases and build risk assessment models in such an alarming situation. The success of a risk assessment model is determined by the variables that are accounted for in building a mathematical model. In this context, attempts must be made to study the role of other environmental variables such as temperature, humidity that vary notably throughout pandemics. Additionally, pathogenic risk groups, host specificity, routes of transmission, infectious dose, communicability, case fatality ratio, and persistence should be considered for risk assessment studies. Moreover, droplet/aerosol concentrations, viral load, infectivity rate, viral viability, lung-deposition probability, and inhalation rate should also be considered in risk assessment studies. Risk mitigation majors, including engineering controls, administrative controls, and personal protective equipment (PPE) should be considered to avoid infections due to SARS-CoV-2.
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 article.

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