Science of the Total Environment 826 (2022) 154182

Contents lists available at ScienceDirect

Science of the Total Environment

journal homepage: www.elsevier.com/locate/scitotenv

Review

The impact of geo-environmental factors on global COVID-19 transmission: A review of evidence and methodology

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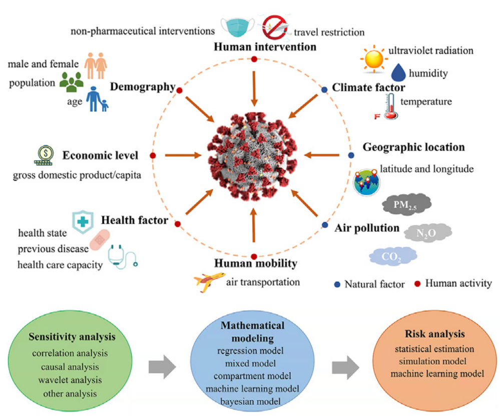
HIGHLIGHTS

- Impact of natural and human factors on global COVID-19 transmission is reviewed.
- Distinct spatiotemporal heterogeneity exists in these impacts.
- Meteorological factors are highly mentioned in early studies.
- Human interventions achieve decisive impacts on global COVID-19 pandemic.
- Methodology includes sensitivity analysis, mathematical modeling and risk analysis.

GRAPHICAL ABSTRACT



ARTICLE INFO

Article history:
Received 8 November 2021
Received in revised form 22 February 2022
Accepted 23 February 2022
Available online 26 February 2022

Editor: Jay Gan

Keywords:
Global COVID-19 transmission
Natural factor
Human activity
Model
Risk analysis

ABSTRACT

Studies on Coronavirus Disease 2019 (COVID-19) transmission indicate that geo-environmental factors have played a significant role in the global pandemic. However, there has not been a systematic review on the impact of geo-environmental factors on global COVID-19 transmission in the context of geography. As such, we reviewed 49 well-chosen studies to reveal the impact of geo-environmental factors (including the natural environment and human activity) on global COVID-19 transmission, and to inform critical intervention strategies that could mitigate the worldwide effects of the pandemic. Existing studies frequently mention the impact of climate factors (e.g., temperature and humidity); in contrast, a more decisive influence can be achieved by human activity, including human mobility, health factors, and non-pharmaceutical interventions (NPIs). The above results exhibit distinct spatiotemporal heterogeneity. The related analytical methodology consists of sensitivity analysis, mathematical modeling, and risk analysis. For future studies, we recommend highlighting geo-environmental interactions, developing geographically statistical models for multiple waves of the pandemic, and investigating NPIs and care patterns. We also propose four implications for practice to combat global COVID-19 transmission.

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http://dx.doi.org/10.1016/j.scitotenv.2022.154182

Contents

1. Introduction

Since December 2019, the emergence and rapid spread of acute respiratory infectious diseases caused by the novel coronavirus have triggered an internationally unprecedented public health crisis. This novel coronavirus —severe acute respiratory syndrome coronavirus 2 (SARS-CoV-2) comes from the beta coronavirus family and is similar to SARS-CoV-1 in genome sequence (Cohen and Normile, 2020). On February 11, 2020, the World Health Organization (WHO) officially named the infectious disease caused by SARS-CoV-2 Coronavirus Disease 2019 (COVID-19) (WHO, 2020b). This disease can be transmitted through contact and respiration and shows high human-to-human transmissibility compared with other coronavirus infectious diseases (Chan et al., 2020; Shereen et al., 2020). On March 12, 2020, the WHO declared COVID-19 a global pandemic (WHO, 2020a). COVID-19 has caused severe pneumonia outbreaks on a worldwide scale. As of 5 January 2022, 4:53 pm CET, a total of 293,750,692 confirmed cases, including 5,454,131 deaths have been reported (WHO, 2022). Among them, the number of COVID-19 cases and deaths in the Americas ranks first in the world, and multiple waves of COVID-19 have occurred in Europe (WHO, 2022).

Global COVID-19 presents a distinct spatial distribution. Some countries have been experiencing a limited growth and spread of COVID-19, while others are suffering from widespread community transmission and nearly exponential growth of infections (Dong et al., 2020). Throughout the international fight against the COVID-19 pandemic, many researchers have found that outbreaks are related to a variety of geo-environmental factors, including climate factors, and human activity; most of them show evidence that human activity plays a dominant role in COVID-19 transmission. On the one hand, human activities have been conceived as a critical driver for the spread of previous infectious diseases (Wu et al., 2014), and human interventions may blunt COVID-19 transmission (Amuedo-Dorantes et al., 2021). To effectively combat COVID-19 transmission, most countries have issued diverse intervention policies such as border lockdowns, self-isolation, and limited gatherings; evidence from China indicates that strict intervention measures are highly effective means of inhibiting the spread of COVID-19 (Tian et al., 2020). In addition, urban sectors and factors have had an impact on the spread of COVID-19 (Sharifi and Khavarian-Garmsir, 2020). Social composition and politics in cities are critical factors influencing COVID-19 infections (Barak et al., 2021). On the other hand, climate change shows a significant effect on infectious diseases (Li et al., 2018; X. Wu et al., 2020; Wu et al., 2016). Cold and dry weather conditions aggravate COVID-19 transmission, since human resistance to infectious diseases becomes weaker and longer staying indoors increases the possibility of closer contact with people who carry the virus (Kronfeld-Schor et al., 2021; Naumova, 2006; Y. Wu et al., 2020). Weaker ultraviolet-B radiation may contribute to COVID-19 transmission in 152 countries (Moozhipurath et al., 2020). Further, due to the time required for pathogen reproduction and incubation, meteorological factors have up to a 14-day lag effect on the incidence of COVID-19 (Guo et al., 2020).

There are abundant studies on the association between global COVID-19 transmission and geo-environmental factors. However, systematic reviews on this topic have rarely been conducted. Some research has examined the impact of specific geo-environmental factors on the spread of COVID-19 in certain countries or a short period, but less is known about the impact of geo-environmental factors on COVID-19 transmission at a global scale. Thus, we address three questions in this review:

(1) What are the impacts of geo-environmental factors on global COVID-19 transmission, and what are the characteristics of these impacts?
(2) How have the interactions of geo-environmental factors affected the global spread of COVID-19?
(3) Which methods can be used to quantitatively assess these impacts and perform risk analysis for the future?

We aim to review the impacts of geo-environmental factors on global COVID-19 transmission and related methods to quantitatively evaluate the above impacts in order to propose suggestions for both research and practice.

2. Method

We focused our literature search on the impacts of geo-environmental factors on the global transmission of COVID-19. We followed the basic

Table 1
The lists of keywords used for literature screening.

Set	Category	Keyword
Aspects of global COVID-19 transmission	Three aspects of COVID-19 transmission	Global, globe, world, continent, countries, severe acute respiratory syndrome coronavirus, Coronavirus Disease 2019, COVID-19 transmission, case, mortality, death, recovery, SARS-CoV-2, outbreak, incidence, pandemic
Impact of geo-environmental factors on global COVID-19 transmission	Natural factors	Air pollution, geographic location, climate factor (e.g. temperature, humidity, precipitation, wind speed, ultraviolet radiation, air pressure)
	Human activities	Human mobility, health factor (e.g., Global Health Security Capabilities (GHS), obesity, smoking, previous disease burden, economic level, socioeconomic factor, demography, non-pharmaceutical interventions (NPIs))
Environment-based methodology on global COVID-19 transmission	Sensitivity analysis	Global, Coronavirus Disease 2019, COVID-19, linear correlation, wavelet analysis
	Environment-based COVID-19 mathematical models	Global, Coronavirus Disease 2019, COVID-19, model, regression, mixed model, compartment model, machine learning
	Risk analysis	Global, Coronavirus Disease 2019, COVID-19, case, transmission, incidence, outbreak, projection, prediction, risk analysis

aspects of a systematic review, including literature sources, search strategy, screening procedure, eligibility criteria, results synthesis, and they primarily comply with Systematic Reviews and Meta-Analyses (PRISMA) guidelines.

For the full index of related studies, we searched the available literature from commonly used databases, including the Web of Science Core Collection. We also searched the PubMed and GreenFILE databases to obtain the latest studies in the biomedical and environmental fields. In order to identify studies that are not retrieved from these databases, we also searched literature from Google Scholar.

The keywords for literature selection contain three categories, and all returned literature had to include at least one of the categories (Table 1). The first category describes the aspects of global COVID-19 transmission, which primarily include COVID-19 cases, mortality, and recovery. The second category involves the impact of geo-environmental factors on global COVID-19 transmission. The third category entails environment-based methodology. Keywords mainly contain mathematical models for examining the geo-environmental effects on global COVID-19 and risk analysis of global COVID-19 incidence. All keywords used for the literature search are outlined in Table 1. Additionally, we designed a comprehensive search string that consisted of combinations of searched keywords in two key categories, as shown below: ("COVID-19" OR "SARS-CoV-2" OR "Coronavirus") AND ("Natural environment" OR "Climate factor" OR "Human activit*" OR "Socioeconomic factor") AND ("Sensitivity" OR "Model" OR "Risk") AND ("Global" OR "Country" OR "Continent"). The guiding framework is depicted in Fig. 1.

The article screening procedure is illustrated in Fig. 2. We applied eligibility criteria (inclusion/exclusion criteria) to different stages of the literature screening. First, we preliminarily identified a total of 1,849 studies using three categories of search terms. Second, based on the inclusion and exclusion criteria whereby geo-environmental factors influence global COVID-19 transmission, we removed literature focusing on the impact of COVID-19 on geo-environmental factors. Third, through a further review of the titles, abstracts and themes, we excluded another 737 studies since they chiefly centered on medical research, clinical diagnosis, therapeutic solutions, mental health, and secondary trauma. Finally, after reviewing the full text of the remaining literature, we synthesized the results and included a total of 49 published items in the review.

3. The impact of geo-environmental factors on global COVID-19 transmission

3.1. Preliminary analysis of the included literature

Dominant journals and title terms included for this review can be observed in the Sankey diagram in Fig. S1; it depicts dominant journals in each year and their relationships with main terms extracted from titles. In addition, the frequent keywords included for this review are shown in Fig. S2, and the size of each term represents its frequency of occurrence. It is clear that most existing studies have adopted COVID-19, temperature, SARS-CoV-2, and humidity as keywords, focusing on the impacts of climate factors on the global COVID-19 pandemic.

3.2. Evidence

In the context of geography, we categorize environmental factors into two types: the natural environment and human activity. Global COVID-19 transmission has primarily been affected by geo-environmental factors,

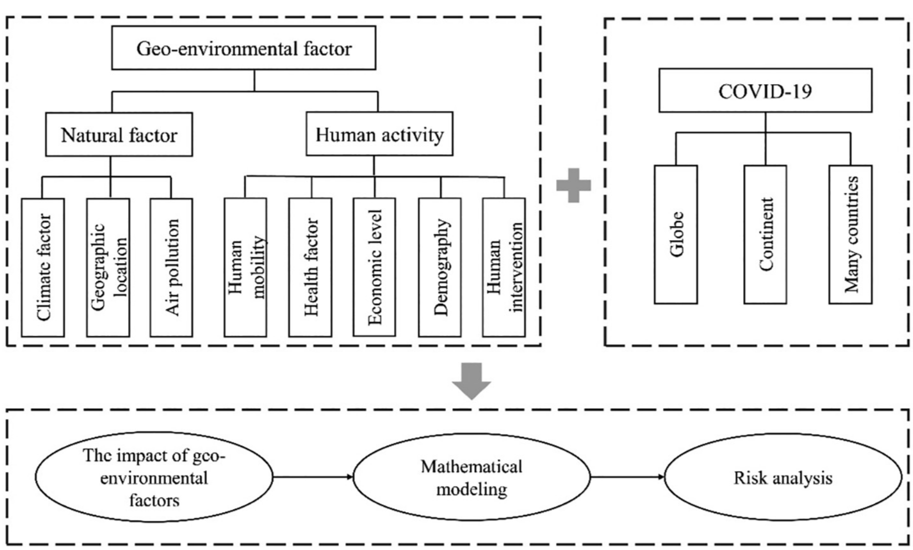

Fig. 1. The transmission of global COVID-19, the impact of geo-environmental factors, mathematical modeling and risk analysis.

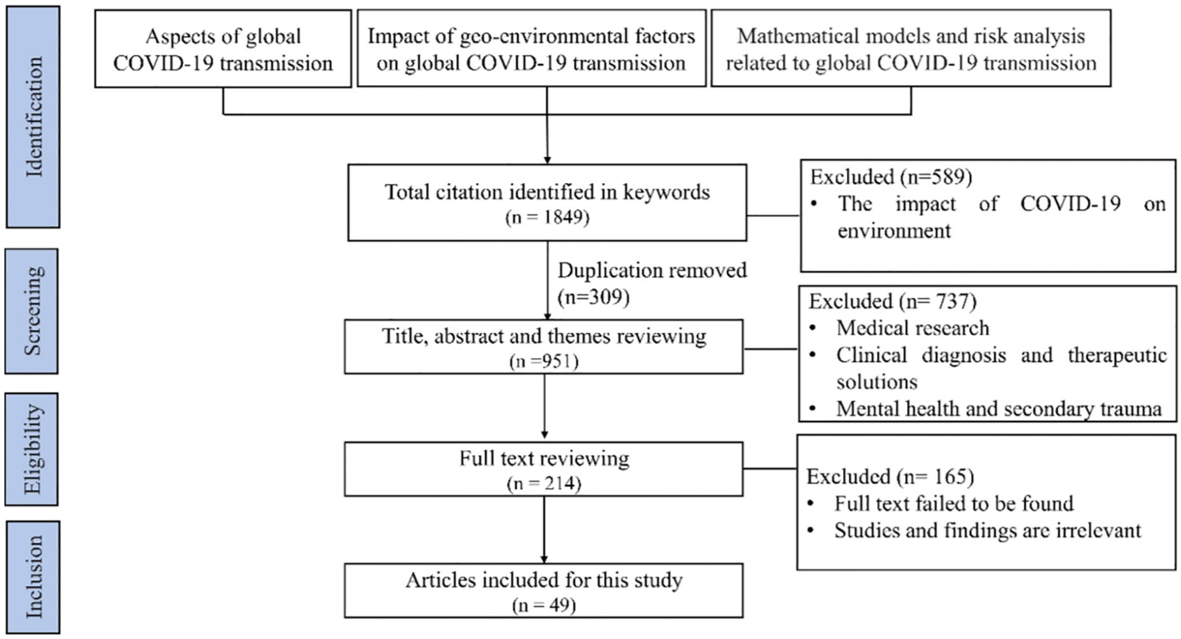

Fig. 2. Procedure of literature identification, screening, eligibility and inclusion.

including the natural factor, human activity (Fig. 3 and Table S2), and their interactions. A proportion of the cited to total literature for geo-environmental factors is provided in Table S1, indicating that existing studies have paid more attention to the impact of climate factors, human interventions, and demography on global COVID-19 transmission.

3.2.1. The impact of natural factors on global COVID-19 transmission

3.2.1.1. Climate factors

Temperature

Temperature is a frequently mentioned influential climate factor of global COVID-19 transmission (Table S2 and Fig. 3). First, the average temperature is negatively associated with global COVID-19 incidence. Temperature has a significantly negative association with confirmed cases or the mortality of COVID-19 (Guo et al., 2020; M. Li et al., 2021; Sarmadi et al., 2020; Sobral et al., 2020; Tzampoglou and Loukidis, 2020; Y. Wu et al., 2020), but is positive for recovery cases in 20 countries/regions with the top confirmed COVID-19 cases as of April 27, 2020 (Sarkodie and Owusu, 2020). One study conducted in 154 countries indicates that high temperature can be more effective in mitigating COVID-19 transmission than low temperature (M. Li et al., 2021). Second, there is a non-linear association between temperature and global COVID-19 transmission. One study performed in 127 countries suggests that temperature lower than 20 °C is negatively correlated with the daily new cases of

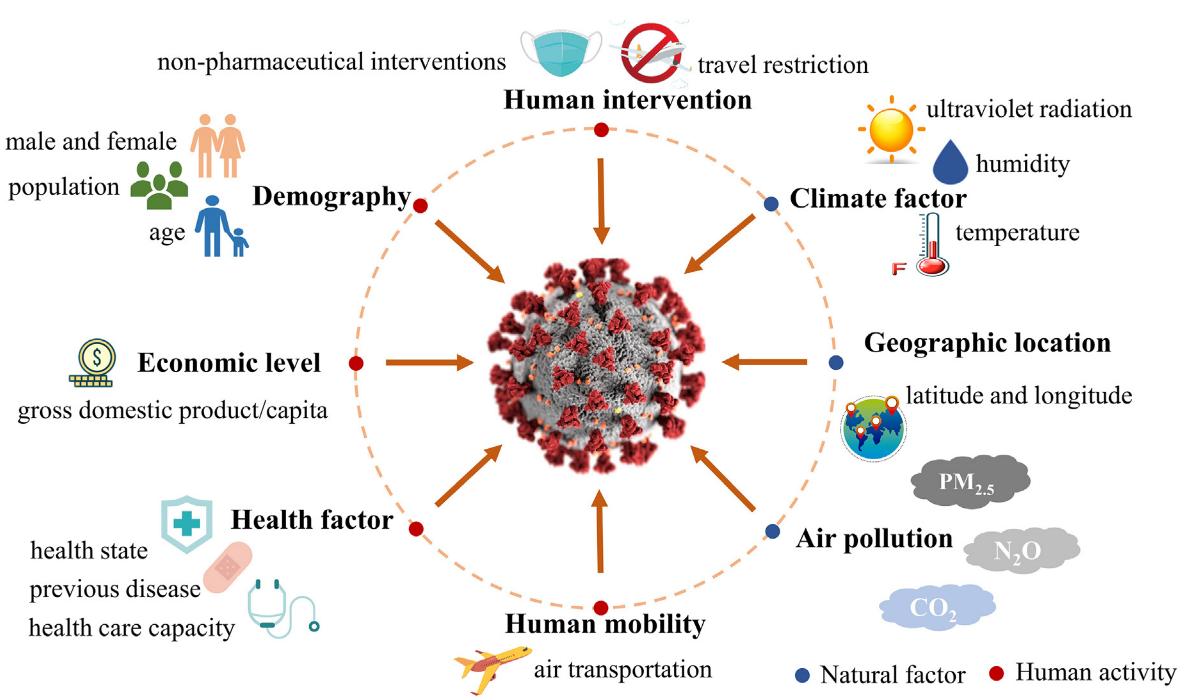

Fig. 3. Impact of main geo-environmental factors on global COVID-19 spread.

COVID-19; and temperature higher than 20 °C is positively correlated with daily new cases (Yuan et al., 2020). Third, the impact of temperature on global COVID-19 transmission is weak. One study reports that there is no significant correlation between temperature and COVID-19 transmission in 8 countries (Pan et al., 2021). One study indicates that there is no significant association between cumulative effects of temperature and COVID-19 growth rates across 173 countries (Carleton et al., 2021). COVID-19 mortality shows no significant association with temperature (Sobral et al., 2020). Although lower temperatures may promote COVID-19 transmission in 154 countries (M. Li et al., 2021), the rise in temperature has been insufficient to inhibit the global pandemic. Hence, when the weather becomes warmer, the number of confirmed COVID-19 cases fails to decline substantially across 8 countries (Pan et al., 2021) and 277 regions (Su et al., 2020).

Ultraviolet radiation

Ultraviolet radiation has been protective in slowing the COVID-19 pandemic (Table S2 and Fig. 3). Ultraviolet-B radiation promotes skin synthesis of vitamin D, which may improve human immunity and decrease the probability of critical COVID-19 cases (Moozhipurath et al., 2020). Ultraviolet radiation has a significantly negative effect on COVID-19 transmission in 152 countries (Moozhipurath et al., 2020), 173 countries (Carleton et al., 2021), 128 countries, and 98 provinces/states (Merow and Urban, 2020); the impact reaches a peak after ultraviolet radiation exposure for 9 to 11 days in 173 countries (Carleton et al., 2021).

Humidity

Humidity has played an important role in the global COVID-19 pandemic, and its effect has been heterogeneous (Table S2 and Fig. 3). Relative humidity is negative for confirmed COVID-19 cases and deaths in 20 countries (Sarkodie and Owusu, 2020) and 166 countries (Y. Wu et al., 2020), and is positive for recovery cases in 20 countries (Sarkodie and Owusu, 2020). Further, absolute humidity ranging from 5 to 10 g/m^3 may have marked the peak of viral transmission in 206 countries/regions through April 20, 2020 (Islam et al., 2021). However, no significant correlation between COVID-19 transmission and humidity is found across 8 countries (Pan et al., 2021) and in 100 countries (Meyer et al., 2020). The cumulative effects of humidity also show an insignificant association with COVID-19 growth rates in 173 countries (Carleton et al., 2021).

Other climate factors

Other climate factors impacting global COVID-19 incidence include precipitation, wind speed, surface pressure, average daylight hours, dew/frost point, and cloud clover (Table S2). First, the results concerning the impact of precipitation on the global COVID-19 pandemic are not consistent. Some studies imply that precipitation has a positive association between the number of confirmed cases and deaths, but a negative association with the number of recovery cases in 20 countries (Sarkodie and Owusu, 2020). While a study indicates that there is a weak association between cumulative precipitation and total cases per million and total deaths per million of COVID-19 across 101 countries (Tzampoglou and Loukidis, 2020). Second, the impact of wind speed on global COVID-19 is twofold. One study conducted in 419 sites from 190 countries indicates that compared with temperature the impact of wind speed on the incidence of COVID-19 is weak (Guo et al., 2020). A notable negative association is found between 14-day-lagged wind speed and COVID-19 transmission in 206 countries/regions (Islam et al., 2021); while wind speed is positive for daily new cases and deaths, but negative for daily recovery cases in 20 countries (Sarkodie and Owusu, 2020). A study performed in 127 countries indicates that wind speed below 7 m/s is negative for daily new cases of COVID-19 (Yuan et al., 2020). Additionally, one study indicates that surface pressure is significantly positive for daily new cases and deaths but negative for the daily recovery cases in 20 countries (Sarkodie and Owusu, 2020). Third, the average daylight hours are negative for global COVID-19 transmission. The average daylight hour has played a protective role in the number of total confirmed COVID-19 cases and deaths in over 210 countries and territories (Iqbal et al., 2020). Fourth, the dew/frost point is positive for global COVID-19 cases. The dew/frost point exhibits a significantly positive association with COVID-19 cases and deaths, and a significantly negative association with recovery cases in 20 countries (Sarkodie and Owusu, 2020). Fifth, cloud cover has no significant association with global COVID-19 incidence. A weak association is found between cloud cover and COVID-19 incidence and mortality among 101 countries (Tzampoglou and Loukidis, 2020).

3.2.1.2. Geographic location. Geographic location is a determining factor affecting global COVID-19 cases and deaths (Table S2 and Fig. 3). One study suggests that COVID-19 transmission shows a significantly positive relationship with latitude while negative relationship with longitude (Sarmadi et al., 2020). In contrast, one study indicates that latitude is negative to COVID-19 spread while longitude is positive to COVID-19 in 154 countries (M. Li et al., 2021). However, a study suggests that almost equal distribution of COVID-19 cases is obtained in high, low and middle latitudes and a weak association is found between latitude and COVID-19 cases at the global level (Jamshidi et al., 2020).

3.2.1.3. Air pollution. Air pollution has affected the COVID-19 pandemic; reported pollutants mostly include $PM_{2.5}$, N_2O, CO_2 and Aerosol Optical Depth (AOD). First, both $PM_{2.5}$ and N_2O are positive for global COVID-19 cases and mortality (Table S2 and Fig. 3). A significant portion of global COVID-19 mortality is attributable to anthropogenic air pollution, and $PM_{2.5}$ is a key cofactor in increasing the risk of global COVID-19 death (Pozzer et al., 2020). One study indicates that $PM_{2.5}$ is significantly positive for COVID-19 cases in African countries and Asian countries (Chakraborti et al., 2021). Another study performed in 8 Asian countries indicates that higher mortalities of COVID-19 are observed in areas with long-term exposure to $PM_{2.5}$ (Baniasad et al., 2021). A significantly positive association is found between average annual exposure to $PM_{2.5}$ air pollution and the initial growth rate of COVID-19 cases, in the countries with at least a six-day period of no less than 30 COVID-19 cases per day (Duhon et al., 2021). Likewise, N_2O has a significantly positive association with COVID-19 mortality in European and Oceania countries (Chakraborti et al., 2021). Second, the results concerning the impact of CO_2 on the COVID-19 pandemic are inconsistent. Total CO_2 emissions show a significantly positive association with COVID-19 mortality in American and African countries (Chakraborti et al., 2021). In contrast, there is no significant association between the number of COVID-19 cases and CO_2 trends in approximately 160 countries and territories (Eltoukhy et al., 2020) and AOD in 8 Asian countries (Baniasad et al., 2021).

3.2.1.4. The interaction of natural factors. The interaction of climate factors has been significant in mitigating the global COVID-19 pandemic. Interactive factors include ultraviolet radiation, air temperature, and humidity. First, temperature, combined with ultraviolet light, is positive for COVID-19 transmission. Temperature combined with ultraviolet light positively affects the COVID-19 growth rate across 128 countries and 98 states and provinces (Merow and Urban, 2020). Second, relative humidity is synchronized with temperature to affect COVID-19 incidence. Even though relative humidity alone fails to affect COVID-19 cases, its impact appears to be noticeable if the temperature is below a certain threshold and relative humidity in a certain range (Tzampoglou and Loukidis, 2020). The severity of the COVID-19 epidemic seems to intensify in 101 countries when the relative humidity ranged from 60 to 80% and the air temperature is below 15 °C (Tzampoglou and Loukidis, 2020). Third, the interactive effect of temperature and humidity on COVID-19 incidence is not notable. A global study expects that a biased association is found between warmer weather and COVID-19 cases (Jamshidi et al., 2020). This indicates that equivalent temperature (i.e., the comprehensive effect of temperature and humidity) fails to significantly correlate with the proportion of COVID-19 infections, except for the eastern Mediterranean, while the association in the eastern Mediterranean is significant but low (Jamshidi et al., 2020). Moreover, at the national level, the association between equivalent temperature and the COVID-19 transmission rate is not consistent across countries. Specifically, the association is positive in the USA, Italy, and India but negative in China, Brazil, and Australia (Jamshidi et al., 2020).

The interaction of geographic location and climate factors

As a primary factor influencing climate conditions, geographic location plays a vital role in driving global COVID-19 incidence. Island countries with humid weather are positive for COVID-19 cases and mortality (M. Li et al., 2021).

3.2.2. The impact of human activity on global COVID-19 transmission

3.2.2.1. Human mobility. Human mobility is a key factor influencing the COVID-19 pandemic, including migration, air transportation, and major sporting events (Table S2 and Fig. 3). Migration has had a strong effect on confirmed COVID-19 cases. One study carried out in 8 Asian countries suggests that lower mobility can inhibit the COVID-19 transmission rates with a 6-day lag (Baniasad et al., 2021). Specifically, the refugee population shows a strong association with COVID-19 cases in American countries (Chakraborti et al., 2021). Net migration is positive for COVID-19 cases across Oceania countries (Chakraborti et al., 2021). The population of arrivals in approximately 160 countries and territories may have a significant effect on COVID-19 cases (Eltoukhy et al., 2020). Additionally, registered air transport is significantly, positively correlated with COVID-19 mortality in European states (Chakraborti et al., 2021). Another study indicates that flight passenger traffic is positive for COVID-19 cases and deaths in 154 countries (M. Li et al., 2021). Likewise, major sporting events promote the spread of COVID-19 in European countries (M. Li et al., 2021).

3.2.2.2. Health factors. Health factors frequently affect COVID-19 transmission (Fig. 3), including health state, previous disease burden, and health care capacity (Table S2).

Health state

Health state is a central factor impacting not only human infection, but also people's recovery from global COVID-19 (Table S2 and Fig. 3). Higher Global Health Security Capabilities (GHS) is positively associated with COVID-19 recovery cases in 50 countries (Chaudhry et al., 2020) while is positively related to COVID-19 growth, in the countries with at least a six-day period of no less than 30 COVID-19 cases per day (Duhon et al., 2021). In addition, some health indices are influential for the global COVID-19 pandemic. First, obesity prevalence is positively correlated with global COVID-19 incidence. Higher obesity prevalence is significantly associated with increased COVID-19 cases and mortality in 50 countries (Chaudhry et al., 2020). There is a negative association between the percentage of the population with BMI < 18 and COVID-19 mortality in 154 countries (M. Li et al., 2021). Second, the findings concerning the impact of smoking prevalence on COVID-19 are inconsistent. Higher smoking prevalence is associated with a reduction in critical cases in 50 countries (Chaudhry et al., 2020), suggesting that smoking has played a protective role in COVID-19 incidence in 154 countries (M. Li et al., 2021). In contrast, one study indicates that higher smoking prevalence is positive for COVID-19 mortality in 39 countries (Pan et al., 2020). Another study indicates that the significant association between smoking and COVID-19 deaths is not found in 154 countries (M. Li et al., 2021).

Previous disease burden

Previous disease burden has been a crucial health factor for global COVID-19 infection (Table S2 and Fig. 3). One study estimates that the unmitigated COVID-19 pandemic scenario results in 6.1%, 3.8% and 13.3% of COVID-19 infections, occurring in patients with cardiovascular disease (CVD), chronic obstructive pulmonary disease (COPD) and diabetes (Walker et al., 2020). Diabetes is strongly, non-linearly positive for COVID-19 cases in African countries (Chakraborti et al., 2021). In contrast, one study carried out in 154 countries suggests that the human immunodeficiency virus (HIV) infection is negative for COVID-19 transmission (M. Li et al., 2021). Further, life expectancy is significantly positive for COVID-19 cases in European countries (Chakraborti et al., 2021) and for transmission rate of COVID-19 in 277 regions (Su et al., 2020).

Health care capacity

Health care capacity is central to mortality and recovery status following infection with COVID-19. Related factors include the number of nurses, doctors, hospital beds, and CT scanners; the test/detection capacity of COVID-19; and quality oxygen support (Table S2 and Fig. 3). The number of nurses is negatively correlated with increased COVID-19 mortality in 50 countries (Chaudhry et al., 2020). The number of hospital beds is negative for COVID-19 mortality in 154 countries (M. Li et al., 2021). Likewise, one study performed in 39 countries suggests that CT scanners may play a protective role in decreasing COVID-19 mortality (Pan et al., 2020). In terms of the test/detection capacity of COVID-19, early detection capacity is significantly positive for COVID-19 incidence in 100 countries (Meyer et al., 2020). Similarly, the COVID-19 test number shows a negative association with COVID-19 mortality in 169 countries, especially in those countries with fewer hospital beds (Liang et al., 2020), while the rate of COVID-19 testing has an insignificant association with the number of critical cases or overall mortality in 50 countries (Chaudhry et al., 2020). Moreover, one study carried out in more than 100 countries indicates that the deficiency in quality oxygen support disproportionately may raise COVID-19 fatality in young people (Walker et al., 2020).

3.2.2.3. Economic level. Economic level is a determining factor for COVID-19 infection (Fig. 3); reported factors include per capita gross domestic product (GDP), domestic income dispersion, and ease of doing business (Table S2). First, per capita GDP is positive for global COVID-19 transmission except for some African countries. Per capita GDP is significantly, positively associated with mortality in 50 countries (Chaudhry et al., 2020), while per capita GDP has a negative association with COVID-19 cases and deaths in African countries (Chakraborti et al., 2021). Second, domestic income dispersion fails to mitigate global COVID-19 transmission. Reduced domestic income dispersion negatively affects increased COVID-19 mortality in 50 countries (Chaudhry et al., 2020). Third, the ease of doing business may be protective for COVID-19 growth at an early stage of pandemic. The ease of doing business index shows a negative association with the COVID-19 growth rate, in countries with at least a six-day period of no less than 30 COVID-19 cases per day (Duhon et al., 2021).

3.2.2.4. Demography. Human demography is essential for heterogeneity in different groups and for identifying vulnerable populations. Demographic factors include population, gender, age, residence pattern and family size (Table S2 and Fig. 3).

Population

The population is also a critical demographic factor influencing not only global COVID-19 incidence, but also mortality (Table S2 and Fig. 3). One study shows that the total population shows a significant association with COVID-19 cases and mortality in Asian countries (Chakraborti et al., 2021). In particular, the total population is significantly positive for COVID-19 mortality in European countries (Chakraborti et al., 2021). Moreover, the proportion of urban people is positive for COVID-19 cases but negative for its mortality in 154 countries (M. Li et al., 2021). Populations of more than 1 million urban agglomerations are positive for the COVID-19 growth rate, in the countries with at least a six-day period of no less than 30 COVID-19 cases per day (Duhon et al., 2021). However, no significant association is found between population density and total COVID-19 cases and deaths in 101 countries, with Human Development Index (HDI) > 0.7 (Tzampoglou and Loukidis, 2020).

Gender

Sex is highly mentioned among demographic factors affecting global COVID-19 mortality (Table S2 and Fig. 3). Although COVID-19 cases in males and females had no significant difference, men are almost three times more likely to need access to an intensive treatment unit (ITU) in 47 countries (Peckham et al., 2020). In addition, the sex ratio (male/female) is positive for COVID-19 deaths in 154 countries (M. Li et al., 2021).

Age

Age has been primary in the global COVID-19 pandemic (Table S2 and Fig. 3). The median population age is significantly positive for COVID-19 cases in 50 countries (Chaudhry et al., 2020) and for COVID-19 mortality in 101 countries (Tzampoglou and Loukidis, 2020). Likewise, the percentage of the population over 70 years old increases the COVID-19 death rate in 39 countries (Pan et al., 2020). The proportion of the elderly is positive for transmission rate of COVID-19 in 277 regions (Su et al., 2020) and COVID-19 mortality in 169 countries (Liang et al., 2020). In contrast, the proportion of people aged younger than 10 is negative for COVID-19 cases in 154 countries (M. Li et al., 2021). The proportion of infants who start breastfeeding notably reduces COVID-19 cases in 53 African countries (Okeahalam et al., 2020).

Residence pattern and family size

Residence pattern and family size have affected the subsequent transmission of COVID-19 within and between families (Table S2). In African nations and some Asian states, the residence patterns of older people have increased their vulnerability to COVID-19 fatality owing to intrafamily transmission (Esteve et al., 2020). Southern European nations, all else equal, are the most vulnerable to COVID-19, influenced by their aging populations and high degrees of intergenerational residence (Esteve et al., 2020).

3.2.2.5. Human interventions. Human interventions have been fundamental to the global COVID-19 pandemic (Table S2). Related measures include NPIs, travel restrictions, and public service and traffic infrastructure.

NPIs

NPIs are instrumental in controlling global COVID-19 transmission (Table S2 and Fig. 3), mostly encompassing border closures; lockdowns; school, workplace, and commercial business closures; night-time curfews; bans on public events; restrictions on gathering and internal movement; and contact tracing and facial coverings (Table S2). One study performed in 6 countries (China, South Korea, Italy, Iran, France and the United States) finds that NPIs show a significant impact on decreasing daily COVID-19 growth rates (Hsiang et al., 2020). Border closures have a significant impact on restricting COVID-19 transmission across border countries, and are associated with the time and extent of closures. Longer time to border closures from the first reported case is associated with increased COVID-19 cases in 50 countries (Chaudhry et al., 2020). Lockdowns have a profound effect on slowing down COVID-19 transmission in Europe (Flaxman et al., 2020), but neither border closures nor full lockdowns show any association with COVID-19 mortality in 50 countries (Chaudhry et al., 2020). Moreover, decreasing contact in crowds effectively prevents the spread of COVID-19. Decreasing contact in large populations, such as through school and workplace closures, limiting gatherings, and bans on public events, help to slow COVID-19 transmission in 175 countries and regions (Askitas et al., 2021) and 131 countries (Y. Li et al., 2021), while the impact of introducing and canceling individual policies lags by 1 to 3 weeks (Y. Li et al., 2021). A few NPIs, including closing all educational services, shutting down non-essential businesses, and limiting gatherings of up to 10 people, are significantly associated with decreased COVID-19 transmission in 41 countries (Brauner et al., 2021). Night-time curfews commonly adopted during the second COVID-19 wave also help to reduce disease transmission in Europe (Sharma et al., 2021). Additionally, internal movement restrictions have a strong association with decreased COVID-19 infection in 130 countries and regions (Y. Liu et al., 2021). Contact tracing is the optimal strategy to exit COVID-19 pandemic circumstances in 8 Asian countries (Baniasad et al., 2021). Facial coverings are protective for mitigating COVID-19 growth rates in 133 countries (Ge et al., 2021). Notably, a combination of NPIs is more effective than a single intervention in slowing COVID-19 transmission in 41 states (Brauner et al., 2021). However, both workplace closures and limited gatherings are not significantly associated with the COVID-19 growth rate, in nations with at least a six-day period of no less than 30 COVID-19 cases per day (Duhon et al., 2021). Stay-at-home orders in 41 countries (Brauner et al., 2021), internal mobility reductions and public transport closures in 175 countries and regions (Askitas et al., 2021) show negligible effects on COVID-19 transmission.

Travel restrictions

The findings concerning the effect of air travel restrictions on the risk of transmitting COVID-19 are inconsistent (Table S2 and Fig. 3). One study performed in 136 countries shows that travel restrictions have a significant effect on COVID-19 prevalence in most countries in May 2020, and the number of imported cases accounts for more than 10% of the total incidence assuming no reduction in air travel volumes (Russell et al., 2021). Another study indicates that the Wuhan travel ban can effectively slow down global COVID-19 pandemic and simulates that strict international travel restriction shows an only modest impact on COVID-19 transmission (Chinazzi et al., 2020). However, one study suggests air travel restrictions based on reduction in flight passenger volume would only make a minor contribution to the prevention of virus importation across 28 countries (Shi et al., 2020). Closing further 10 travel hub airports has a similar effect as decreasing global passenger traffic to prevent countries' imported risk of COVID-19 (Shi et al., 2020).

Public service and traffic infrastructure

Public service and traffic infrastructure have also been significant intervention factors influencing COVID-19 infections and deaths (Table S2). The government effective score is negative for COVID-19 mortality in 169 countries (Liang et al., 2020). In contrast, the transport infrastructure quality score is positive for COVID-19 mortality across 169 countries (Liang et al., 2020). Likewise, the length of railway is positive for COVID-19 cases and deaths, while vehicle usage is negative for COVID-19 mortality in 154 countries (M. Li et al., 2021).

3.2.2.6. The interaction of human factors. The interaction of human factors has played a dominant role in slowing down global COVID-19 incidence, including the interaction of economic level and health, the interaction of economic level and demography, and the interaction of health and demography.

The interaction of economic level and health

First, the interaction of country income and previous disease burden has affected COVID-19 mortality. One study performed in 87 countries indicates that previous disease burden measured by disability-adjusted life years (DALYs) is significantly associated with the COVID-19 mortality in high-income countries but there is no association in non-high-income countries (Lianga et al., 2020). Specifically, after controlling for other factors, in 45 high-income nations, DALYs for Alzheimer's disease and other types of dementia, circulatory diseases, and COPD are significantly and positively correlated with COVID-19 mortality (Lianga et al., 2020). Second, the interaction of country income and health care capacity has affected COVID-19 infection and mortality. In a study performed in more than 100 countries, such limited health care as capacity intensive care beds, mechanical ventilators and oxygen, may increase COVID-19 fatality in low-income countries, counteracting the protective effects of young people (Walker et al., 2020). Another study carried out in 169 countries indicates that there is a more significantly negative association between the number of test and COVID-19 fatality in low-income countries and countries with fewer hospital beds (Liang et al., 2020).

The interaction of economic level and demography

The interaction of income and age has been a crucial factor influencing COVID-19 transmission. Inflammatory aging and immune aging make elderly individuals susceptible to viruses. One study conducted over 100 countries estimates that a larger proportion of COVID-19 fatalities to occur in those aged 40 and above in low-income and low-middle-income countries (Walker et al., 2020). Moreover, the COVID-19 incidence of elderly people in low-income countries is higher than that of elderly people in high-income groups and middle-income countries (Walker et al., 2020). In particular, the share of the population over 65 is positive for COVID-19 mortality in 45 high-income countries (Lianga et al., 2020). The significantly positive relationship between COVID-19 transmission and GDP is due to the significantly positive correlation between the population aged over 65 and GDP in 277 regions (Su et al., 2020).

The interaction of demography and health

First, the interaction of the aging population and previous disease burden increases the risk of COVID-19 incidence. COVID-19 mainly leads to lung infection and hyperglycemia, which also increase the difficulty of treatment, especially among individuals with previous disease burden, including lung diseases and diabetes. One study conducted over 100 countries assumes that if all countries have the equal healthcare availability, lower-income countries would have a lower COVID-19 mortality due to large young population (Walker et al., 2020). Second, the interaction of smoking and population density is positively correlated with COVID-19 mortality. The deleterious effect of smoking on the COVID-19 fatality rate is significant in 39 countries with high population densities (Pan et al., 2020). Third, the interaction of health state and gender influences the COVID-19 mortality. One study conducted in 209 countries indicates that the percentage of female smokers increases COVID-19 mortality, which may be owing to the discovery that the percentage of female smokers roughly reflects a country's income level (Cao et al., 2020).

3.2.3. The interactive impact of natural and human factors on global COVID-19 transmission

In addition to the interactions of natural factors and the interactions of human activity, the comprehensive interaction of climate factors and human activity has played a crucial role in the global COVID-19 pandemic, including the interaction of temperature and human mobility, the interaction of pre-existing disease and air pollution, and the interaction of previous disease burden and geographic location. First, temperature plays a protective role; however, human mobility is a determining factor in virus transmission. Temperature could be related to behavioral patterns that increase human exposure to the virus and promote the transmission of COVID-19 (Shao et al., 2021). A study in 47 countries indicates that high temperature may promote COVID-19 transmission by increasing human mobility (Shao et al., 2021). The temperature is negatively correlated with COVID-19 transmission but is positively correlated with human mobility, and human mobility increases the risk of COVID-19 transmission (Shao et al., 2021). Second, pre-existing diseases, associated with exposure to air pollution, exacerbate the severity of COVID-19. Air pollution has a negative impact on bronchopulmonary and cardiovascular pre-conditions (including hypertension, coronary artery disease, cardiomyopathy and asthma), which cause a higher risk of mortality of COVID-19 (Pozzer et al., 2020). Third, one study estimates that increased risk of COVID-19 occurs in small island countries with high-incidence of diabetes (Clark et al., 2020).

4. Methodology of examining the effect of geo-environmental factors on global COVID-19 transmission

Many quantitative methods have been adopted to examine the effect of geo-environmental factors on global COVID-19 incidence. According to the research purpose, we classify these methods into sensitivity analysis, mathematical modeling, and risk analysis (Table S3).

4.1. Sensitivity analysis

We use sensitivity analysis to detect the sensitivity of the impact of geo-environmental factors on global COVID-19 transmission; we classify it into four categories (Table S3). The first category includes linear correlation analysis. The related methods include Spearman's correlation (Yuan et al., 2020) and Pearson correlation (Cao et al., 2020). A Spearman's correlation analysis conducted in 127 countries preliminarily suggests that temperature, relative humidity and wind speed show a nonlinear correlation with COVID-19 cases (Yuan et al., 2020). The second category is wavelet analysis (Pan et al., 2021). A time-series wavelet coherence analysis is used to investigate the possible association between meteorological conditions and the basic reproductive number (R_0) of COVID-19 in 198 locations of 8 countries (Pan et al., 2021). The third category is causal analysis. Peter and Clark Momentary Conditional Independence (PCMCI) index is used to quantify causal dependencies between climate factors, air pollution, mobility, government response and COVID-19 transmission in 8 Asian countries (Baniasad et al., 2021). There are other methods for comparing the differences in factors or identifying the dominant factors associated with COVID-19 transmission. Related methods include principal coordinate analysis (PCoA) (Lianga et al., 2020) and the linear discriminant analysis effect size (LEfSe) method (Lianga et al., 2020). In a study conducted in 45 high-income countries and 42 non-high-income countries, PCoA is used to explore whether there are significant differences in previous disease burden between high and low-mortality countries of COVID-19(Lianga et al., 2020). If there is a difference, the causes of significant differences in previous disease burden among high and low-mortality countries are identified using LEfSe method (Lianga et al., 2020).

4.2. Mathematical modeling

The quantitative impact of geo-environmental factors on global COVID-19 transmission has been investigated through modeling (Table S3). The first category entails regression models, including simple linear regression (Liang et al., 2020), multiple linear regression (Y. Li et al., 2021; Liang et al., 2020; Su et al., 2020), fixed effect linear regression model (Moozhipurath et al., 2020), loess regression interpolation approach (Chen et al., 2020), panel data regression (Carleton et al., 2021; Y. Liu et al., 2021; Sobral et al., 2020), time-series regression model (Guo et al., 2020), ordinary least squares (OLS) (Chakraborti et al., 2021), and stepwise regression analysis (Chakraborti et al., 2021). For example, the loess regression interpolation approach is used to detect the relationship between COVID-19 cases and meteorological factors in a time lag series across 15 countries (Chen et al., 2020). Panel data regression is performed to investigate the effect of ultraviolet on daily COVID-19 growth rates in 173 countries (Carleton et al., 2021). The second category is mixed models, including negative binomial regression model (NBRM) (Chaudhry et al., 2020; Okeahalam et al., 2020; Pan et al., 2020), generalized linear mixed model (GLMM) (Meyer et al., 2020; Wang et al., 2020) and generalized additive models (GAM) (Y. Wu et al., 2020). For example, NBRM is suitable to deal with over dispersed dependent variables and it is applied to examine the relationship between some human activity factors and COVID-19 mortality across 39 countries (Pan et al., 2020). A study adopts GLMM to analyze the relationships between temperature and the cumulative number of COVID-19 cases across 429 cities (Wang et al., 2020). In another study, GAM is used to investigate the influence of relative humidity and temperature on the COVID-19 daily new cases and deaths across 166 countries (Y. Wu et al., 2020). The third category is the compartment model, which includes the susceptible-infected-removed (SIR) model (Hsiang et al., 2020; Walker et al., 2020) and the susceptible-exposed-infected-removed (SEIR) model (Baniasad et al., 2021; Walker et al., 2020). The primary difference between the SEIR and the SIR models is that the exposed category is added to the SEIR model, which encompasses people who have been exposed to infected individuals but are not infectious yet (Abou-Ismail, 2020). For example, an age-structured SEIR model is developed to simulate the dynamics of COVID-19 transmission and its need for healthcare over time (Walker et al., 2020). The fourth category is the machine learning model, including Random Forest (RF) and Gradient Boosted Machine (GBM) (Chakraborti et al., 2021). Both RF and GBM are adopted to evaluate the associations between COVID-19 spread and determinant geo-environmental factors in 51 African countries, 45 American countries, 25 Asian countries, 52 European countries, and 7 Oceanian countries, respectively (Chakraborti et al., 2021). The fifth category is the Bayesian model (Ge et al., 2021; Merow and Urban, 2020), which allows for explaining and exploring uncertainty using posterior distribution estimations, and is popular in various forecasting studies (Merow and Urban, 2020). For example, Hierarchical Bayesian model is adopted to explain that 17% of the variation in the maximum COVID-19 growth rates is explained by seasonality, but 19% of variation arises from country-specific factors in 128 countries and 98 provinces/states (Merow and Urban, 2020). These five categories of methods are not used independently in many studies, and multiple methods are adopted, such as machine learning and regression.

4.3. Risk analysis

Risk analysis studies have focused on projecting the potential health risks of COVID-19, affected by significant meteorological and socio-demographic variables. Risk analysis is rooted in different methods and models, including statistical estimation models (Wells et al., 2020), simulation models (Chinazzi et al., 2020; Li et al., 2020; Lin et al., 2020), and machine learning models (Eltoukhy et al., 2020) (Table S3). For the statistical estimation models, one study performed in 63 countries and regions adopts the maximum likelihood approach to calibrate the daily probability of infected people leaving the mainland China by fitting their predictions of exported COVID-19 cases and the international incidence of cases with a travel history in China (Wells et al., 2020). Based on empirical distributions of time from COVID-19 symptom onset to first medical visit and incubation period, the risk of exportation of infected person from the epicenter is assessed using flight data (Wells et al., 2020). For the simulation model, one study conducted in 63 countries develops a two-stage simulation model (First stage: imported cases; Second stage: localized outbreaks) to simulate the spatiotemporal variations in the number of COVID-19 cases and estimate the future global risk (Lin et al., 2020). For the machine learning model, a non-linear autoregressive exogenous input (NARX) based on the time-series model has the ability to predict data in the future by using historical successive data alongside externally affected factors, which is suitable for processing large amounts of data (Boussaada et al., 2018; Eltoukhy et al., 2020). One study adopts NARX neural network-based algorithm to predict the daily new cases of COVID-19 in 20 countries (Eltoukhy et al., 2020).

5. Discussion

5.1. Spatiotemporal heterogeneity

5.1.1. Spatial heterogeneity

The above reviewed evidence indicates that the impact of geo-environmental factors on global COVID-19 transmission shows spatial differences and biases, namely spatial heterogeneity. First, spatial heterogeneity is reflected in different impacts of the same geo-environmental factor on COVID-19 transmission in different countries. For example, N_2O is not significantly associated with COVID-19 deaths in Asia, but is significantly associated with COVID-19 deaths in Europe (Chakraborti et al., 2021). Likewise, there is a significant association between previous disease burden measured by DALYs and COVID-19 mortality in high-income countries, but no such association in non-high-income states (Lianga et al., 2020). Second, the interaction effect of different geo-environmental factors and their isolated effect on COVID-19 transmission varies across countries. For example, temperature is negative to COVID-19 transmission in 190 countries (Guo et al., 2020), while temperature, combined with ultraviolet light, promotes COVID-19 transmission in 128 countries and 98 states and provinces (Merow and Urban, 2020).

5.1.2. Temporal heterogeneity

In addition to spatial heterogeneity, distinct temporal heterogeneity also exists; it refers to clear variations concerning the impact of geo-environmental factors on global COVID-19 transmission over time. First, temporal heterogeneity has been reflected in different effects of the same geo-environmental factors on global COVID-19 at different stages of the pandemic. For example, $PM_{2.5}$ is only positive for COVID-19 growth rates in the early stages of the pandemic, while this relationship has become weak since late March and negligible since mid-April 2020 in 159 countries and territories (Ficetola and Rubolini, 2021). Compared with May 2020, the impact of travel restrictions may have been much weaker by September 2020 (Russell et al., 2021). Second, the variations in key geo-environmental factors in different waves of global COVID-19 transmission cannot be overlooked. For example, the comprehensive effect of NPIs in the first wave is stronger than that in the second wave in 7 countries (Sharma et al., 2021). International travel restrictions show the greatest effectiveness among NPIs in the first wave; then, in the second wave, the most effective NPI is facial covering, which is replaced by restrictions on gathering in the third wave in 133 countries (Ge et al., 2021).

5.2. Implications for research and practice

5.2.1. Implications for research

The thematic map provides specific insight into highlighted themes with reference to the impact of geo-environmental factors on global COVID-19 transmission. We divide it into four parts evaluated by relevance degree (centrality) and development degree (density) in Fig. 4, and

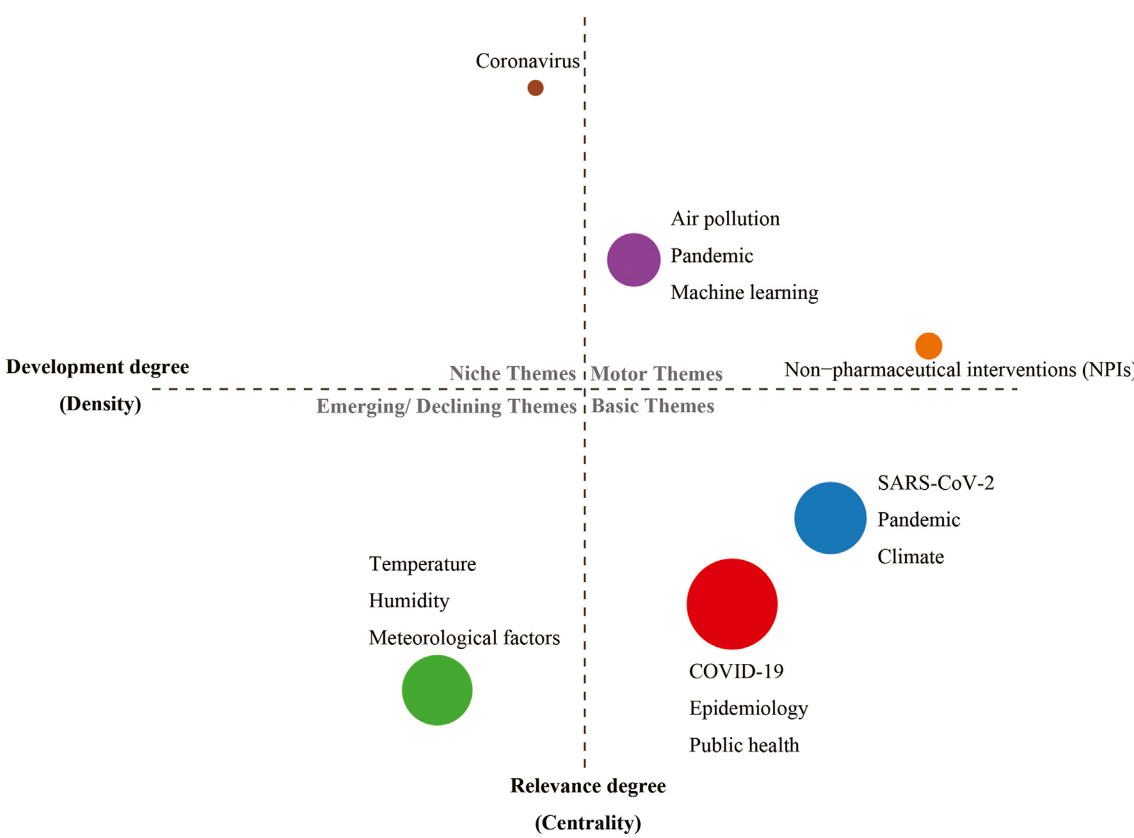

Fig. 4. Thematic map based on keywords of reviewed literature.

keywords in the same clusters show high association. The niche themes on the upper left represent well-developed yet isolated themes; the motor themes on the upper right denote both highly developed and critical themes; the lower right theme is a basic one, which previous studies have extensively investigated; emerging or declining themes are on the lower left part, which may be disappeared or emerged under-developed marginal themes (Verma et al., 2020). As illustrated in Fig. 4, SARS-CoV-2, COVID-19, pandemic, epidemiology, climate, and public health appear to be basic themes. Temperature, humidity and meteorological factors are emerging or declining themes. More studies have investigated the association between global COVID-19 transmission and climate factors; future directions on this topic are challenging. Themes related to the coronavirus are developed but isolated. NPIs are associated with motor themes and more studies are needed to provide deeper insight into this topic. Significantly, pandemic, air pollution, and machine learning are also related to highly developed and important themes. More work should be done to investigate the associations between air pollution and the global COVID-19 pandemic and the application of machine learning in response to the impact of geo-environmental factors on global COVID-19 transmission.

Future research needs to be improved from the following three aspects (Table 2). First, selecting comprehensive and critical geo-environmental factors is essential to address issues of predicting global COVID-19 transmission. Most studies in our literature survey neglect the interactive effect of geo-environmental factors on global COVID-19, only considering the isolated effect of various geo-environmental factors. Moreover, some geo-environmental factors have been perceived as critical in specific-region studies, which fail to consider these factors in most research on global COVID-19 transmission. Some human activities, such as the proportion of people who walk to work in the USA (Luo et al., 2021) and the attributes of city geometry in Hong Kong, China (Kwok et al., 2021), have a notable impact on the spread of COVID-19. Second, appropriate, robust mathematical models should be developed to better explain the relationship between geo-environmental factors and global COVID-19 incidence. Future studies should pay more attention to the spatial-temporal variation in the global spread of COVID-19, given that the COVID-19 data continuously vary over time. For example, multistage COVID-19 models grounded in specific geo-environmental factors need to be developed for high-risk countries during different waves of the epidemic. It is necessary to develop geographically statistical models to fully understand the impact of geo-environmental factors on global COVID-19 transmission (such as the geographically weighted regression [GWR] model in China) (Wu et al., 2021). Third, NPIs and care patterns should be further investigated to minimize the health burden at the global level. On the one hand, epidemiological models can be used to explore the impact of NPIs on COVID-19 transmission at a global scale. For example, one study develops an economy-SEIR coupled model to assess economic losses under various control measures for combatting COVID-19 transmission in Wuhan, China (Chen et al., 2021). On the other hand, investigating the spatiotemporal pattern of care around the world is important. One study employs generalized estimating equations (GEE) models to evaluate variations of therapies used in the United States during April–July 2020 (Fan et al., 2021). Another study uses multiscale GWR to explain spatial nonstationary of COVID-19 vaccination rates in the United States (Mollalo and Tatar, 2021). Therefore, to improve policy responses and care patterns, future studies should provide deeper insight into the multifactorial analysis based on mathematical models.

Table 2
The improved aspects of future research.

Aspect	Example
Select comprehensive and critical geo-environmental factors	• For different population group's infectivity of COVID-19, critical geo-environmental factors or their interactions are different at a global scale. • Some geo-environmental factors have been conceived as important in specific-region studies, which fail to consider these factors in most research on global COVID-19 transmission.
Develop appropriate and robust mathematical models	• Multistage COVID-19 models grounded in specific geo-environmental factors need to be developed for high-risk countries during different waves of the epidemic. • It is necessary to develop geographically statistical models to fully understand the impact of geo-environmental factors on global COVID-19 transmission.
Highlight non-pharmaceutical interventions (NPIs) and care patterns	• Epidemiological models can be used to explore the impact of NPIs on global COVID-19. • Investigating the spatiotemporal pattern of care around the world is important.

5.2.2. Implications for practice

An effective policy response to COVID-19 transmission could minimize current and future threats globally, especially in developing countries with limited health care capacity. From the perspective of geo-environmental factors, there are four important aspects to consider that we recommend in practice (Table 3). First, COVID-19 transmission has a more obvious seasonal cycle at higher latitudes (X. Liu et al., 2021). Lower temperature and weaker ultraviolet radiation increase the risk of COVID-19 transmission. Thus, strict NPIs, such as aggressive social distancing and facial coverings, are conducive to combat COVID-19 transmission in cold weather, especially in high latitude countries with weaker ultraviolet radiation. Second, air pollution, including $PM_{2.5,}$ has exacerbated global COVID-19 transmission (Duhon et al., 2021). CVD, negatively affected by PM air pollution (Hamanaka and Mutlu, 2018), may exacerbate the severity of COVID-19. COVID-19 also may induce and worsen cardiovascular disorders, including arrhythmias and heart failure (Bansal, 2020; Nishiga et al., 2020). Thus, we recommend interventions designed for regions with severe air pollution and high occurrence of CVD, such as appropriate lockdown policies of COVID-19, which also improve air quality (Venter et al., 2020). Third, developing countries with weaker health systems are required to defend against the imported risk of COVID-19. Target measures, including border

Table 3
Policy implications and recommendations related to different geo-environmental factors.

Geo-environmental factors	Policy implications	Practical recommendations
• Climate factors • Geographic location	Lower temperature and weaker ultraviolet-B radiation increase the global COVID-19 incidence (Moozhipurath et al., 2020; Tzampoglou and Loukidis, 2020). The seasonality of COVID-19 transmission is more obvious in higher latitudes (X. Liu et al., 2021).	In cold weather conditions, aggressive social distancing and wearing masks are essential, especially in high latitude countries with weaker ultraviolet radiation.
• Air pollution • Previous disease burden	Air pollution, including $PM_{2.5}$, is positive for global COVID-19 transmission (Duhon et al., 2021). Cardiovascular diseases (CVD), negatively affected by PM air pollution (Hamanaka and Mutlu, 2018), increase the susceptibility and severity of COVID-19.	Lockdown and stay-at-home order are constructive to mitigate the incidence of COVID-19 in the regions with a high concentration of $PM_{2.5}$ and a high occurrence of CVD.
• Human mobility • Economic level	Air passenger traffic is positive for COVID-19 transmission (M. Li et al., 2021). Limited health care may increase COVID-19 fatality in low-income countries (Walker et al., 2020).	Appropriate border controls and travel restrictions help reduce the importation risk of COVID-19 in developing countries with high healthcare burden.
• Residence pattern	In African and some Asian countries, residence patterns of aged people increase their vulnerabilities to COVID-19 fatality owing to intra family transmission (Esteve et al., 2020).	Close contacts with COVID-19 patients, especially household members, are required to be tested and isolated timely.

controls and financial cooperation, are crucial in efforts to combat COVID-19 and reduce the health care burden. Fourth, close contacts of COVID-19 patients, especially household members, need to be tested and isolated timely, which could greatly help to cut off the chain of virus transmission.

6. Conclusion

This paper provides a comprehensive overview concerning the impact of geo-environmental factors on global COVID-19 transmission and emphasizes commonly reported geo-environmental factors, including climate, human mobility, and demographic factors, as well as human interventions. The impact of geo-environmental factors shows distinct spatiotemporal heterogeneity. In addition, this review breaks down existing analytical methodologies into three categories: sensitivity analysis, mathematical modeling, and risk analysis. We provide recommendations for future research based on three aspects: the interactions of critical factors, appropriate and robust mathematical models, and the investigation of NPIs and care patterns. We provide four implications for practice that underline how policies related to geo-environmental factors are needed to better combat global COVID-19 transmission.

CRediT authorship contribution statement

Xiaoxu Wu: Conceptualization. **Danyang Wang and Xiaoxu Wu:** Writing - Original Draft, Investigation, Visualization. **Danyang Wang and Chenlu Li:** Writing- Reviewing and Editing; **Jiatong Han and Jie Yin:** Investigation.

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.

Acknowledgment

This work was supported by the National Key Research and Development Program of China (No. 2012CB955501) and the Fundamental Research Funds for the Central Universities.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.scitotenv.2022.154182.

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