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Review

Environment and COVID-19 incidence: A critical review

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ABSTRACT

The coronavirus disease 2019 (COVID-19) pandemic is an unprecedented worldwide health crisis. Many previous research studies have found and investigated its links with one or some natural or human environmental factors. However, a review on the relationship between COVID-19 incidence and both the natural and human environment is still lacking. This review summarizes the inter-correlation between COVID-19 incidence and environmental factors. Based on keyword searching, we reviewed 100 relevant peer-reviewed articles and other research literature published since January 2020. This review is focused on three main findings. One, we found that individual environmental factors have impacts on COVID-19 incidence, but with spatial heterogeneity and uncertainty. Two, environmental factors exert interactive effects on COVID-19 incidence. In particular, the interactions of natural factors can affect COVID-19 transmission in micro- and macro- ways by impacting SARS-CoV-2 survival, as well as human mobility and behaviors. Three, the impact of COVID-19 incidence on the environment lies in the fact that COVID-19-induced lockdowns caused air quality improvement, wildlife shifts and socio-economic depression. The additional value of this review is that we recommend future research perspectives and adaptation strategies regarding the interactions of the environment and COVID-19. Future research should be extended to cover both the effects of the environment on the COVID-19 pandemic and COVID-19-induced impacts on the environment. Future adaptation strategies should focus on sustainable environmental and public policy responses.

Introduction

COVID-19, a human-to-human infectious disease, is caused by a novel coronavirus called SARS-CoV-2 that can lead to severe viral pneumonia and acute respiratory disease. Patients infected with COVID-19 commonly show the following symptoms: fever, dry cough, and malaise (Wang et al., 2020; Zu et al., 2020). With its high risk of spread, COVID-19 has become the disease with the highest mortality compared with other coronavirus categories, such as Severe Acute Respiratory Syndrome (SARS) and Middle East Respiratory Syndrome (MERS) coronaviruses (Wang et al., 2020). On January 30, 2020, the World Health Organization (WHO) Emergency Committee des-

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ignated COVID-19 as a global health emergency; as of February 8, 2021, COVID-19 had caused at least 105,805,951 confirmed cases and 2,312,278 deaths globally (WHO, 2021).

The COVID-19 pandemic has displayed its severity in the number of confirmed cases and mortality rates all over the world. Some early studies suggest that COVID-19 outbreaks are more likely to happen in high-latitude regions with a colder climate and better socioeconomic conditions, such as some parts of North America and almost all Asian and European countries (Sarmadi et al., 2020). In order to explain its spatial-temporal distribution pattern and manage the control of its transmission worldwide, many researchers have investigated the relationship between environmental factors and COVID-19 occurrence. Generally, in geographical terms, environment factors are categorized into natural environmental factors and human environmental factors (Wu et al., 2021). Some worldwide studies have indicated that both natural and human environmental factors are crucial for COVID-19 transmission and the SARS-CoV-2 virus (Fronteira et al., 2021; Metelmann et al., 2021; Rahimi et al., 2021; Srivastava, 2021). As an airborne transmission pandemic, SARS-CoV-2 and the severity of COVID-19 infection have been proven to be affected by climate conditions and air pollutants (Domingo et al., 2020; Al Huraimel et al., 2020; Nottmeyer and Sera, 2021). Temperature (T) is able to affect the survival and transmission of the virus, and humidity (H) contributes to its viability and persistence when attaching to inanimate objects (Sarkodie and Owusu, 2020; Zarei et al., 2021). T and solar ultraviolet (UV) index in an optimal range show a strong impact on both the spread of the virus and community infections (Gunthe et al., 2020). The wind speed, rainfall and air pressure can affect the survival of SARS-CoV-2 suspended in the air, which may explain the high COVID-19 incidence in countries with a stable meteorological environment (Hossain et al., 2020; Sarkodie and Owusu, 2020). Previous studies indicated that meteorological factors, such as T and wind speed, have a lagged effect on COVID-19 cases and SARS-CoV-2 (Islam et al., 2021). In addition, SARS-CoV-2 transmission by aerosol and fomite is plausible (van Doremalen et al., 2020). Coccia suggested that “air pollution-to-human transmission” is the main mechanism accelerating the transmission dynamics of COVID-19 rather than “human-to-human transmission” (Coccia, 2020b).

Moreover, COVID-19 infections show strong correlations with the human environment. ACE2, expressed by the human body, is the receptor for SARS-CoV-2 entering host cells (Zhou et al., 2020). The SARS-CoV-2 infects people by combining with ACE2, which means that COVID-19 contraction has no bias in favor of age, ethnicity, or gender (Saini et al., 2021). However, the clinical features of COVID-19 patients show that the age, ethnicity, gender and socioeconomic status of patients exhibit a focus on some specific groups (Verity et al., 2020; Pan et al., 2020). Several studies show that patients with a history of pre-existing diseases, such as diabetes, hypertension, etc., have greater odds of COVID-19 mortality (Gold et al., 2020). In the COVID-19 pandemic, health disparities and inequalities have been spotlighted because of financial problems and inequities in access to health services (Nana-Sinkam et al., 2021). As a human-to-human transmission disease, outbreaks of COVID-19 infections occur easily in crowded places, such as densely populated cities and intensive transportation hubs (Ahmadi et al., 2020). Policymakers in different countries have implemented social lockdowns, showing remarkable effectiveness in controlling the transmission dynamics of COVID-19 (Askitas et al., 2021; Candido et al., 2020; Flaxman et al., 2020; Paital et al., 2020).

Monitoring of COVID-19 transmission dynamics is necessary. The transmission dynamics of COVID-19 are mainly described by the basic reproduction number, real-time effective reproduction numbers and fatality rates, indicators which are used by policymakers to find ways to better isolate COVID-19 infected individuals from other people (Yuan et al., 2020; Flaxman et al., 2020 Candido et al., 2020). Evidence of seasonality indicates that climatic variables, such as surface radiation and T, are also associated with the basic reproduction number, though their explanatory power is weaker compared to socioeconomic factors and disease control measures (Metelmann et al., 2021). A more exhaustive and comprehensive index for the transmission dynamics of COVID-19 was suggested considering various parameters such as environmental, demographic, meteorological and health risk factors of cities/regions (Coccia, 2020a). Some comprehensive indicators such as interactional commercial trade, population density, economic dynamism and human mobility are able to well explain the severity of COVID-19 (Bontempi et al., 2021).

Many literature reports have focused on the correlation between certain environmental variables and COVID-19 incidence in specific regions or countries, or presented reviews of literature evidence on the interaction of COVID-19 and natural or social environments, such as the geospatial analysis of COVID-19 or the impact of polluted environments on COVID-19 (Franch-Pardo et al., 2020; Shakil et al., 2020). However, as a global pandemic, COVID-19 is affected by complex environmental conditions, and its interactions with the environment are increasingly significant (Facciolà et al., 2021). More importantly, its impact on human beings and nature can conversely change its spread (Rahimi et al., 2021; Facciolà et al., 2021). Thus, a review on the correlation between COVID-19 and both natural and human environments and their interactions is still needed. Therefore, the motivation for this review is: What is the relationship between COVID-19 incidence and environmental factors? And what are the interactive effects of different environmental factors on the spread of COVID-19?

This review aims to provide a reference for future development of COVID-19 prevention protocols and further research directions and will take a sight in: first, we critically discuss diverse findings on the types of natural and human environment factors affecting COVID-19 incidence at global, country, and city levels, showing its spatial heterogeneity and uncertainty; second, we emphasize the interactive effects of different types of environmental factors on COVID-19 transmission, offering an overall framework that simply explains how multi-factors affect COVID-19 spread; third, we summarize the effect of COVID-19-induced lockdown on the environment in three aspects: air pollution, wildlife activity and socioeconomic development. In addition, after reviewing current research, we also offer some valuable recommendations for future research and adaptation strategies based on COVID-19-environment interactions.

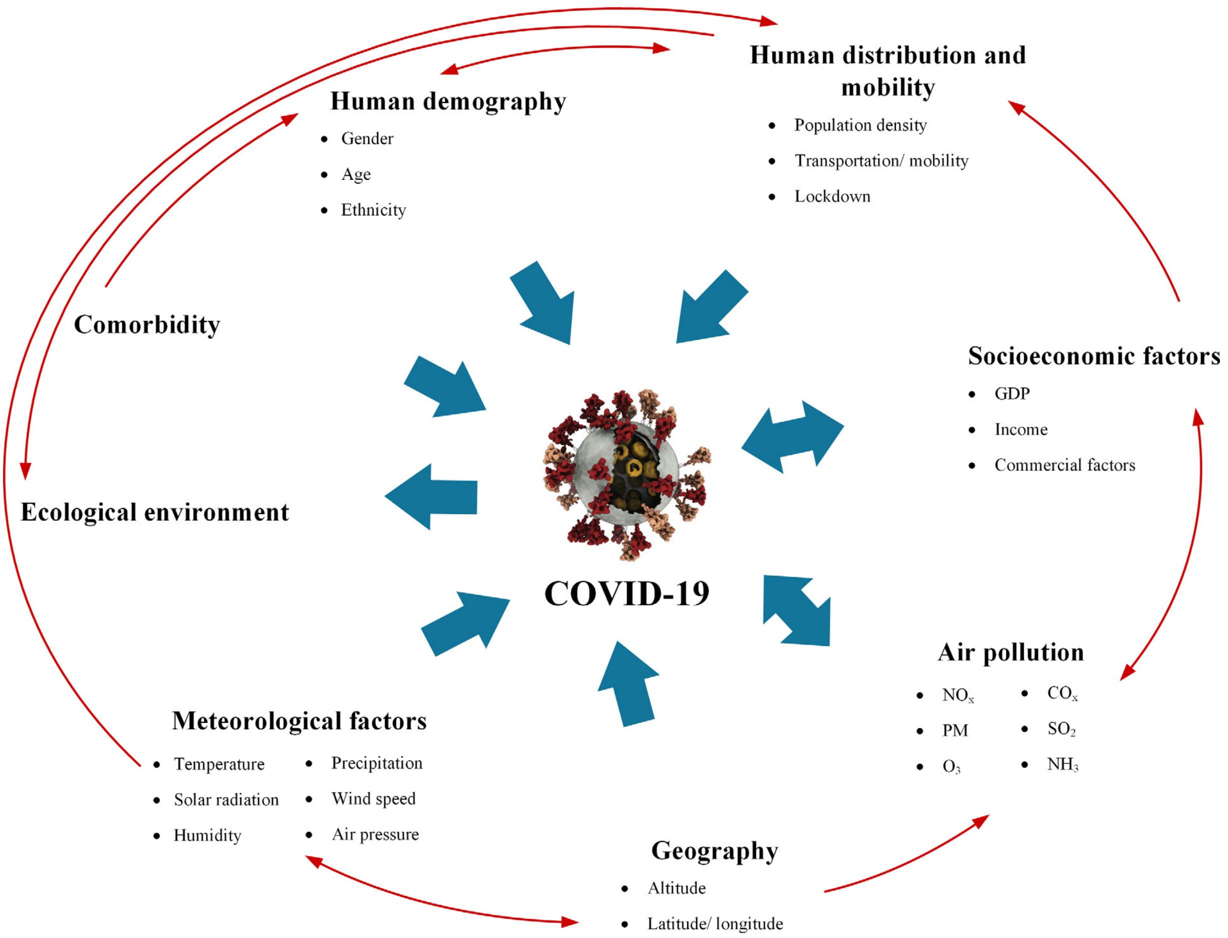

Fig. 1 – Environmental factors and COVID-19. Arrows show their relationships. Blue arrows present relationships between COVID-19 incidence and one type of factor, red arrows present interactive effects among factors on COVID-19. Mono-directional arrows are uni-directional effects on/from COVID-19 or factors, while bi-directional arrows indicate that this single factor can not only affect COVID-19 incidence but also be affected by it.

1. Materials and methods

1.1. *Search strategy*

The review search was guided by a framework (Fig. 1). Two categories of environmental factors were considered, which are natural environmental factors and human environmental factors. Natural environmental factors include meteorological factors, air pollution, the ecological environment, and geography. Human environmental factors include human demography, human distribution and mobility, socioeconomic factors, and comorbidity.

A comprehensive search of literature from 2020 to 2021 was conducted mainly from Web of Science/Knowledge, Elsevier Science Direct, and PubMed. Two sets of terms were used for search keywords to select literature, including: (1) aspects and conditions of COVID-19, such as COVID-19 incidence and SARS-CoV-2; (2) various environmental and human factors, such as Temperature, UV radiation, Humidity, precipitation, wind speed, air pressure, wildlife, endangered animals, altitude, latitude/longitude, NO_x, PM, O_3, CO_x, SO_2, NH_3, gender, age, ethnicity, population density, transportation/mobility, lockdown, gross domestic product (GDP), income, commercial factors and comorbidity. All keywords are listed in Table 1.

The process of literature screening and exclusion is shown in Fig. 2. Initially, 9,250 publications were identified based on keyword searching of the combination of COVID-19 and each environmental factor, and their interactive effects were also included. After limiting the theme in two stages, we eliminated those which were “Medical/therapy study”, “Clinical diagnosis and treatment”, “Psychological trauma related study” and “Technologies exploration study and design”, and 764 articles were left for further screening. By assessing the full text, we excluded repetition, unrelated and unavailable articles, then 302 publications were left for analysis. Finally, 100 articles and reports remained for this review research which are highly relevant to our theme, and most are of high impact from closely related journals. **Appendix A Fig. S1** shows the top 8 publishing journals, and their h- (Hirsch, 2005), g- (Egghe, 2006), and m-indexes (Bornmann et al., 2008).

Table 1 – List of keywords used to select literature.

Sets	Categories	Sub-categories	Keywords
Disease	COVID-19	Aspects and conditions	COVID-19 and incidence (e.g. SARS-CoV-2, the 2019 novel coronavirus, novel coronavirus pneumonia, COVID-19 mortality, COVID-19 confirmed cases)
Environmental factors	Natural environment	Meteorological factors	Climate, weather, meteorological factor, temperature indexes, solar ultraviolet (UV) radiation, humidity indexes, precipitation, rainfall, wind speed, air pressure
		Air pollution	Air quality, air pollution, air pollutants, nitrogen monoxide (NO), nitrogen dioxide (NO_2), particulate matter (PM), $PM_{2.5}$, PM_{10}, carbon emission, carbon dioxide (CO_2), carbon monoxide (CO), sulfur dioxide (SO_2), ammonia (NH_3), ozone (O_3)
		Ecological environment	Wildlife, animals, birds, endangered animals
		Geography	Geography, distribution, altitude, elevation, DEM, plain, longitude, latitude,
	Human environment	Human demography	Gender, age, people of advanced age, race, ethnicity, BAEM, healthcare workers.
		Human distribution and mobility	Population, population density, human mobility, travel restrictions, transport, lockdown, quarantine, transportation, traffic
		Socioeconomic factors	GDP, income, socioeconomic factor, poverty, economy, financial condition, commercial factors, exporting and importing
		Comorbidity	Comorbidity, pre-existing diseases, clinical features

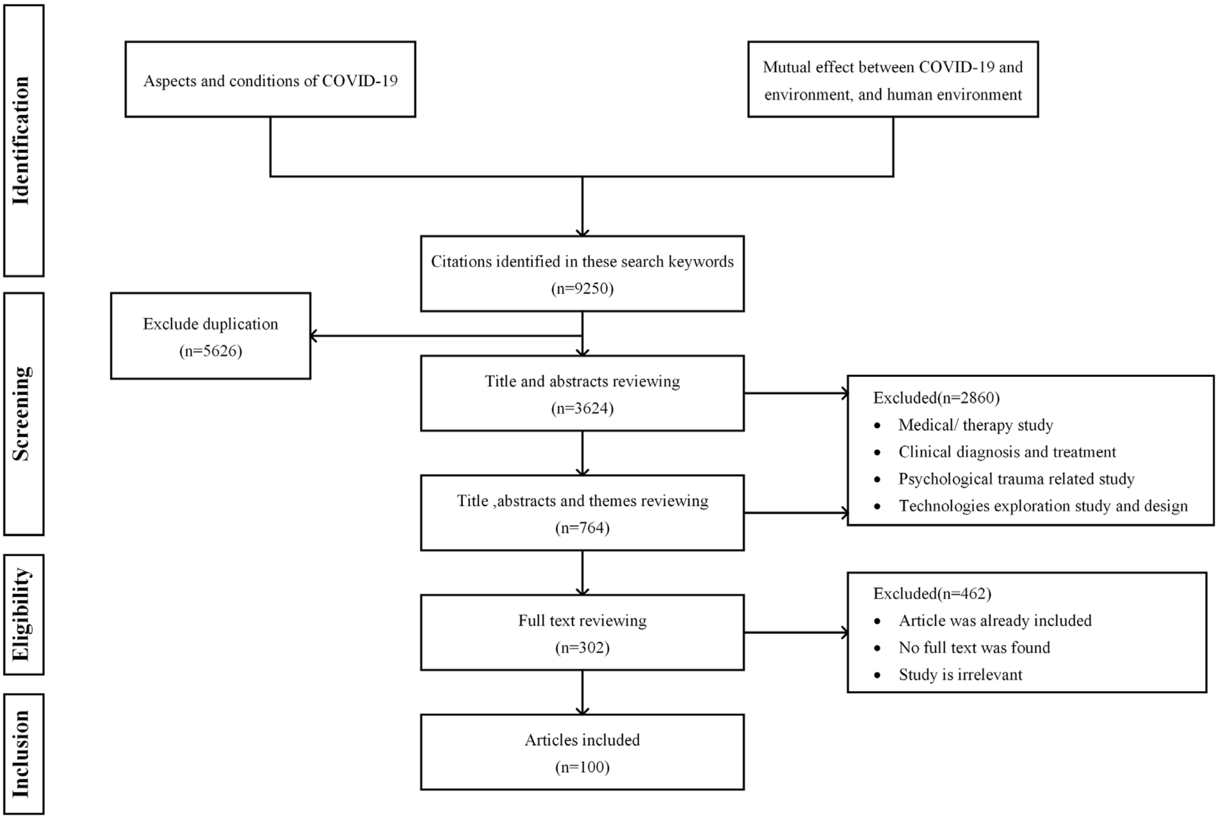

Fig. 2 – Process of literature identification, screening, exclusion and inclusion.

1.2. *Meta-analysis*

In this review, meta-analysis was applied to determine the correlation between average temperature (Ave T) and COVID-19 daily confirmed cases. We collected studies that expressed their relationship as a correlation coefficient (COR). A total of 15 regions in 7 countries were included (**Table S1**). In order to make the data more suitable for meta-analysis, we transformed Spearman's COR into Pearson's COR (Rupinski and Dunlap, 1996). A Fisher transformation was firstly used to convert Pearson's COR into an approximately normal distribution (ZCOR). To account for the heterogeneity of COR from different studies, a standard I-squared test was used for qualification. A random-effect model was used to explain the heterogeneity among and within studies. Meta-analysis was conducted with the software R (version 4.1.0) (Balduzzi et al., 2019; Wei et al., 2015).

2. Results

The relation between the environment and COVID-19 incidence was built guided by three themes. The first theme (3.1) focuses on the impact of environmental factors on COVID-19. We summarize meteorological factors, air pollution, geography, human demography, human distribution and mobility, socioeconomic factors and comorbidity as crucial influencing factors. The second theme (3.2) is the interactive effect of the environment on COVID-19, including interactions of natural environmental factors, human environmental factors and both natural and human environmental factors separately. The third theme (3.3) is the impact of COVID-19 induced lockdowns on air pollution, the ecological environment and socioeconomic factors.

2.1. *Impact of environment factors on COVID-19*

2.1.1. *Meteorological factors*

The relationship between COVID-19 incidence and reported meteorological factors is presented in **Table S2**. Temperature (T) is a crucial and highly-mentioned meteorological factor for the COVID-19 pandemic, in global, country, and city-level studies. In different studies, the relationship was investigated using different T indices (**Appendix A Table S2**). Firstly, a negative correlation between T and propagation of COVID-19 was proposed, but the impact of T indices on COVID-19 incidence showed spatial heterogeneity. Worldwide evidence revealed that the incidence of COVID-19 is inversely/negatively related to T (Guo et al., 2020; Sobral et al., 2020). The negative correlation is sensitive, and even 1°F changes in Ave T can affect the incidence of COVID-19 infections (Sobral et al., 2020). From December 1, 2019 to February 11, 2020, there was a significantly negative association between daily Ave T and daily COVID-19 confirmed cases in Hubei province (Qi et al., 2020). However, the spatial heterogeneity of the impact of T was apparent. One study in China indicated that the impact of Ave T on COVID-19 incidence was mostly positive in Hubei, Hunan, and Anhui provinces but negative in Zhejiang and Shandong provinces, and mixed in Guangdong, Henan, Jiangxi, Jiangsu, and Heilongjiang provinces (Shahzad et al., 2020). Another study in China showed that the effect of mean T on COVID-19 incidence showed varying degrees in different cities, where the correlations respectively strengthened from the west to the east and from the north to the south (Wu et al., 2021). Evidence from 20 countries suggests that disaggregated T, such as maximum T and minimum T, are more helpful than Ave T for understanding the nexus between COVID-19 and T (Sarkodie and Owusu, 2020). A study found that the median value of T played no role in COVID-19 cases in New South Wales, Australia (Ward et al., 2020). However, a study in China indicated that Ave T was the only meteorological factor significantly associated with the COVID-19 transmission rate and that the relationship was negative and exponential (Lin et al., 2020). A meta-analysis (**Fig. 3**) shows a positive correlation (ZCOR) between Ave T (ZCOR = 0.36, 97.43%, 95% CI: 0.03-0.62) and COVID-19 daily cases at the city level, and the ZCOR values indicate spatial heterogeneity. Secondly, an effective impact of T on the COVID-19 infection was determined within some specific T ranges in different regions. A worldwide study indicated that the optimal T range for COVID-19 transmission is 5-15°C, and the peak is 11°C (Huang et al., 2020). In China, a city-level study suggested 8.5°C as the positive-negative dividing line (Wu et al., 2020). In (sub)tropical countries, studies in the cities of Brazil indicated a negative linear relationship in the range 16.8-27.4°C (Prata et al., 2020), while the range from 26.1°C to 28.6°C was significantly correlated with the COVID-19 incidence rate in Jakarta, Indonesia (Tosepu et al., 2020). Thus, although the evidence above broadly confirms that T affects the COVID-19 pandemic, due to its uncertainty, the idea that the COVID-19 pandemic diminishes with the approach of warmer weather falls apart under closer scrutiny (Bashir et al., 2020; Haque and Rahman, 2020; Xie and Zhu, 2020).

Solar radiation is another crucial factor for COVID-19 transmission, and many studies show that UV radiation can reduce COVID-19 incidence (**Table S2**). Global studies show that as the UV index increases, the number of COVID-19 cases decreases (Gunthe et al., 2020). High solar radiation decreased COVID-19 spread/infectivity in some countries or provinces such as Italy (Isaia et al., 2020) and Ontario, Canada (To et al., 2021b). As for the coronavirus itself, a study in Iran found that solar radiation threatens the survival of coronavirus (Ahmadi et al., 2020). However, no significant association was found between UV radiation and COVID-19 transmission in Chinese cities (Yao et al., 2020).

Humidity (H) is also a key factor affecting COVID-19 incidence (**Table S2**). H had a negative correlation with COVID-19 outbreaks in countries such as Iran, England and China (Ahmadi et al., 2020; Liu et al., 2020b; Nottmeyer and Sera, 2021). H is associated with the number of COVID-19 cases on the 7th and 14th lag days in China (Liu et al., 2020b). A negative correlation between H and COVID-19 was observed. Relative humidity (Rh) and the COVID-19 incidence have an inverse J-shaped correlation worldwide (Guo et al., 2020). In Iran, H had a negative correlation with the virus outbreak speed (Ahmadi et al., 2020). However, studies in some other regions produced the opposite result. In Brazil, a higher intermediate Rh was favorable for the COVID-19 transmission rate (Auler et al., 2020). In New South Wales, each 1% drop in Rh predicted a 6.11% rise in the number of COVID-19 cases (Ward et al., 2020). However, according to studies in China,

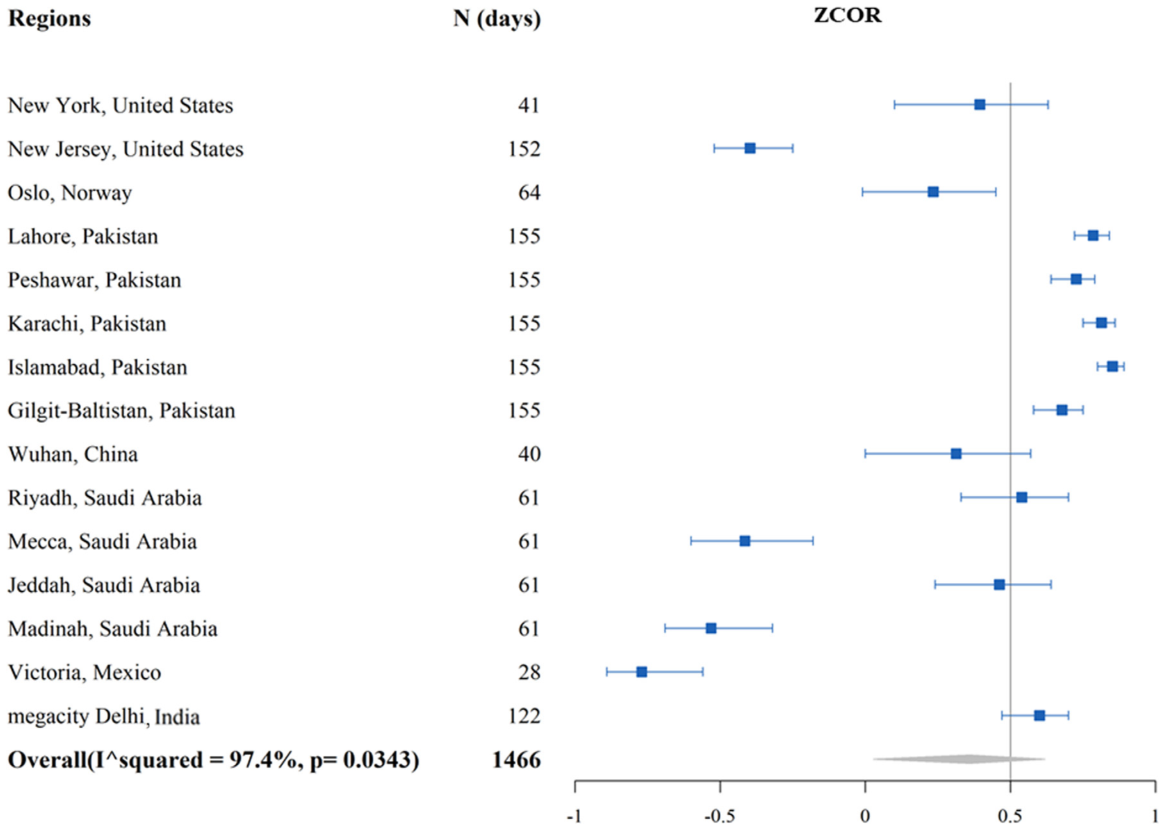

Fig. 3 – Meta-analysis for the correlation (ZCOR) between COVID-19 daily cases and the Ave T at the city level. "Regions" is the list of various cities from different countries. "N(days)" indicates the number of days. The overall ZCOR is 0.36 (95% CI: 0.02-0.62).

when H increased, the COVID-19 virus spread faster (Wu et al., 2021).

The impact of wind speed on the spread of COVID-19 shows an obvious spatial heterogeneity (**Table S2**). A negative relationship between wind speed and COVID-19 incidence was seen in most studies. Worldwide studies have concluded that the relationship between wind speed and COVID-19 spread is negative (Guo et al., 2020). In Iran, COVID-19 outbreaks were more likely to happen at low wind speed (Ahmadi et al., 2020). Similar results were seen in some country-level studies, including in China (Qiu et al., 2020), India, and Sri Lanka (Hossain et al., 2020). In addition, a study in China demonstrated that when the wind speed decreased in the range of 1.5-2.5 m/s, the risk of COVID-19 spread decreased; otherwise, it increased (Wei et al., 2020). However, a study in Turkey involving a time series demonstrated that higher average wind speed over a period of 14 days had the strongest and highest positive correlation with COVID-19 cases (Sahin, 2020). In New York, the correlation was positive but with no statistical significance (Bashir et al., 2020).

Some findings in different countries showed that precipitation decreased COVID-19 spread (**Table S2**). For example, in India, rainfall had a negative effect on COVID-19 confirmed cases (Hossain et al., 2020). In China, when cumulative precipitation was 50 mm or higher, it decreased the risk of COVID-19 transmission (Wei et al., 2020). Despite this, a worldwide study demonstrated that rainfall boosts the spread of COVID-19, and every 1 inch/day increase led to 56.01 more cases per day (Sobral et al., 2020).

Air pressure generally promotes COVID-19 incidence (**Table S2**). In India, air pressure had a positive correlation with estimates of the time-dependent basic reproduction rate COVID-19 (Kulkarni et al., 2020). In China, a significant positive correlation between air pressure and COVID-19 incidence was reported in a city-level study (Wu et al., 2021).

2.1.2. *Air pollution*

Air pollution is another crucial factor impacting the incidence of COVID-19. It has been found to have the greatest actual impact on COVID-19 casualties across the world (Chakraborti et al., 2020). According to a global study, the decline in air pollution during the lockdown led to the avoidance of about 99,270 to 146,649 premature COVID-19 deaths among 76 locations (Liu et al., 2020a). Exposure to air pollution has been seen to increase the risk of COVID-19 incidence in China (Xu et al., 2020a) and England (Travaglio et al., 2020). Every specific pollutant, including NO_x, PM, O_3, CO_x, SO_2, and NH_3, drives the spread of the COVID-19. **Fig. 4** indicates their impact on the COVID-19 pandemic, with most studies focusing on PM and NO_x (Copat et al., 2020; Ali and Islam, 2020). In fact, PM and NO_x can affect both the life cycle of SARS-CoV-2 and triggering of the body's immune system, leading to severe COVID-19 spread and lethality (Woodby et al., 2021; Ali and Islam, 2020).

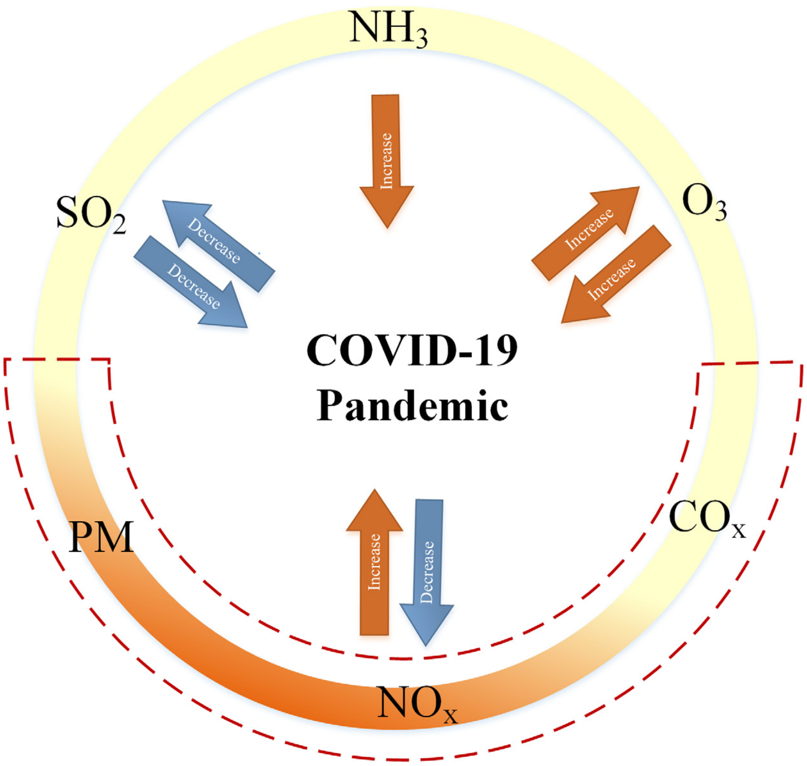

Fig. 4 – Air pollutants and COVID-19. The relationships between individual air pollutants and the COVID-19 pandemic are indicated by orange and blue arrows. The orange arrows indicate increasing effects. The blue arrows indicate decreasing effects. Air pollutants surrounded by red dotted lines share a similar relationship with the COVID-19 pandemic. The colored ring indicates the studies' focus. As the yellow color darkens, more studies are focused on the corresponding air pollutant.

NO_x plays a vital role in both COVID-19 infection and its fatality. For example, a study in England found that higher NO_2 and NO levels increased the number of cases of COVID-19 and deaths (Travaglio et al., 2020), and in London, NO_2 concentrations were found to have a strong correlation with COVID-19 incidence (Sasidharan et al., 2020). Furthermore, as the length of exposure to NO_x increases, higher concentrations of NO_2 can cause more and more severe COVID-19 incidence. For example, in China, every 10 µg/m^3 increment of NO_2 concentration was associated with a 6.94% increase (95% CI: 2.38-11.51%) in the number of COVID-19 confirmed cases (Zhu et al., 2020). In England, an increment of only 1 m^3 in the average NO_2 levels led to an increase of 4.5% (95% CI: 5.99-3.05%) in COVID-19 cases, and for NO, approximately 2% more cases (95% CI: 2.92-1.35%) (Travaglio et al., 2020).

PM is another air pollutant that increases COVID-19 incidence. Cities like Chennai, India (Laxmipriya and Narayanan, 2020) and London (Sasidharan et al., 2020), and regions in England (Travaglio et al., 2020) have witnessed the fact that PM contributes to the death of COVID-19 patients. Both PM_{10} and $PM_{2.5}$ contributed to COVID-19 cases, and the effect of $PM_{2.5}$ may have been greater than that of PM_{10}. For short-term exposure to PM, every 10 µg/m^3 increment in the concentrations of $PM_{2.5}$ (2.24%, 95% CI: 1.02-3.46%) and PM_{10} (1.76%, 95% CI: 0.89-2.63%) increased the number of COVID-19 confirmed cases in China (Zhu et al., 2020). For long-term exposure, every 1 m^3 increase in $PM_{2.5}$ and PM_{10} led to 12% and 8% growth in COVID-19 cases in England (Travaglio et al., 2020). However, $PM_{2.5}$ played no role in the COVID-19 mortality rate at the municipality level in Colombia (Rodriguez-Villamizar et al., 2020). Moreover, PM showed a threshold effect on COVID-19 incidence in different countries and cities. The sensitivity of the relationship of PM concentration to COVID-19 newly confirmed cases was examined in 9 countries from 3 continents, among which Russia, England, Germany, and France found greater sensitivity (Liu et al., 2021). Also, the $PM_{2.5}$ concentration thresholds for preventing and controlling infection in these 9 countries were different (**Appendix A Fig. S2**). In France, to reduce COVID-19 transmission and death, the PM_{10} concentration in Paris, Lyon, and Marseille respectively should be kept below 29.6 µg/m^3, 20.6 µg/$m^{3,}$ and 20.6 µg/m^3 (Magazzino et al., 2020).

Other air pollutants like O_3, CO_x, and NH_3 can also lead to higher numbers of COVID-19 confirmed cases or mortalities, while the concentration of SO_2 shows a reverse effect. A study in Delhi found that O_3 and NH_3 may impact COVID-19 mortality (Sethi and Mittal, 2020). Another study showed that O_3 increased the number of COVID-19 deaths in England (Travaglio et al., 2020). Some vivo studies proved that exposure to O_3 may enhance lung damage and inflammation induced by SARS-CoV-2 (Woodby et al., 2021). A short-term exposure study in China indicated that every 10 µg/m^3 increment in the concentrations of O_3 and CO (4.76%, 95% CI: 1.99-7.52%) increased the number of COVID-19 confirmed cases, while every 10 μg/m^3 increment in the concentration of SO_2 (7.79%, 95% CI: -14.57%–1.01%) decreased confirmed cases (Zhu et al., 2020). CO_2 emission profoundly contributes to COVID-19 cases, and the relationship shows heterogeneity across continents (Chakraborti et al., 2020).

2.1.3. *Geography*

The patterns of COVID-19 transmission are related to geographical location. As the altitude rises, the effect on COVID-19 is muted. In Peru, a reduction in COVID-19 infection was found as the altitude increased, while its case-fatality rate was independent of altitude (Segovia-Juarez et al., 2020). In China, the cumulative number of COVID-19 infection cases dropped as the altitude increased (Sun et al., 2020a). However, the mean altitude, in China's city-level study, was positively correlated with COVID-19 incidence (Wu et al., 2021). In addition, geographic parameters were also related to the spread of COVID-19. Latitude showed a negative relationship with COVID-19 spread in China, while no relation was found for longitude (Sun et al., 2020b).

2.1.4. *Human demography*

Age is likely to affect both the COVID-19 infection rate and mortality rate over a wide range. In some worldwide research studies, the age of COVID-19 incidence was found to range from 10 to over 80 (Verity et al., 2020). The median age of COVID-19 patients was mostly over 40. The mean age of patients at Jintanshan hospital in Wuhan, China, Spain and US infected healthcare workers was 55.5 (Chen et al., 2020), 70 (Berenguer et al., 2020) and 42 (CDC COVID-19 Response Team, 2020), respectively, while a study in Malaysia found a median age of 34 in their sample (Sim et al., 2020). COVID-19 infection and its severity show an age-related distribution. Worldwide studies analyzed patients with positive test results, emphasizing that elders were more vulnerable and more prone to death than younger people, and need more protection (Calderon-Larranaga et al., 2020; Verity et al., 2020). In China, the overall infection fatality ratio increased with age, with patients 80 or older the most likely to be hospitalized (Verity et al., 2020).

Gender is a crucial factor in identifying vulnerable groups for COVID-19. In general, male patients are more affected than females. Males accounted for 71.7% of 5,889 infected cases in Malaysia (Sim et al., 2020), 61% of 3,987 cases in Spain (Berenguer et al., 2020), and 67% of total cases in Wuhan Jinyintan hospital, China (Chen et al., 2020). Male sex is recognized as one of the factors associated with COVID-19 mortality in the UK (de Lusignan et al., 2020). For healthcare workers, the majority of patients are female. The clinical characteristics of healthcare workers in the US indicate that 73% of COVID-19 cases in this group are female (CDC COVID-19 Response Team, 2020). This trend is also found in Italy, Spain and Germany (Rozenberg et al., 2020). However, the COVID-19 positive test rate is comparable for males and females, with no obvious gender difference (Rozenberg et al., 2020).

Ethnicity is increasingly implicated in COVID-19 outcomes, because of both biological and socio-economic mechanisms (Pan et al., 2020). In the COVID-19 pandemic, we have seen the following pieces of evidence. Black, Asian and Minority Ethnic (BAEM) individuals are under a greater risk for contracting COVID-19 (Kirby, 2020). Most studies suggest that they are at an increased risk of infection by SARS-CoV-2 compared to White individuals (Pan et al., 2020). In England, a study indicated that 62.1% of Black people who were tested for SARS-CoV-2 showed a positive result, followed by Asian (30.9%) and White (15.5%) people (de Lusignan et al., 2020). The weathering hypothesis has been used to explain racial disparities in health conditions under chronic exposure to social and economic disadvantages (Forde et al., 2019). For example, the vulnerabilities of African Americans in the US are exacerbated by disparities in exposure to the virus, chronic health conditions and access to treatment once the disease develops because of their low socioeconomic status or lack of economic stability (Saini et al., 2021).

2.1.5. *Human distribution and mobility*

COVID-19 is confirmed to be a human-to-human respiratory infection (Zu et al., 2020), thus population density plays a crucial role in its spread. The trend that dense population causes more spread of COVID-19 was respectively proven in Iran (Ahmadi et al., 2020), Turkey (Sahin, 2020) and China (Zu et al., 2020). A study on the plains area in China showed that high population density can increase the risk of COVID-19 transmission, and the relationship is non-linear (Lin et al., 2020). However, as effective government intervention was implemented, especially in China (Sun et al., 2020a), the impact of population density on COVID-19 spread was minimized, which was also revealed in a country-level study (Diao et al., 2021). Human mobility plays a significant contributing role in COVID-19 transmission, and as population mobility increases in cities, the reproduction numbers of the cities become higher (>1), which means a growing epidemic (Candido et al., 2020). There have been three major human mobility patterns during the COVID-19 pandemic. Firstly, air transportation has been the dominant path in the international spread of COVID-19, creating optimal conditions for COVID-19 emergence and spread (Barouki et al., 2021). For example, studies suggest that airports provided a way for COVID-19 to spread from one country, such as mainland China, to other countries (Wells et al., 2020). Secondly, human migration between cities increases the risk of COVID-19 domestic transmission, especially from COVID-19 foci. In Iran, intra-provincial movement was found to be significantly correlated with high COVID-19 infection rates (Ahmadi et al., 2020). In China, the scale of human migration alone caused marked increases in COVID-19 incidence in 75.6% of cities, and this trend could be found in almost all the provinces (Wu et al., 2021). Moreover, evidence in China indicated that population flow from Wuhan to other cities before lockdown significantly increased the COVID-19 case numbers in destination cities in the following months (Kraemer et al., 2020; Qiu et al., 2020); population flow from Wuhan caused COVID-19 risk to increase more than 50% in 130 cities and over 99% in the 4 largest mega-cities, such as Beijing, Guangzhou, Shenzhen and Shanghai (Du et al., 2020). Accordingly, the number of transportation facilities carrying people from Wuhan was significantly positively associated with the number of infected COVID-19 cases, such as railways (1.40), freeways (2.07), national highways (1.31), and airports (1.70) (Wei et al., 2020) before January 23, 2020. Thirdly, transportation within a single city is negatively correlated with the risk of SARS-CoV-2 infection and spread. For example, in China, the travel intensity within a city has a negative correlation with the city-level COVID-19 incidence (Qiu et al., 2020; Wu et al., 2021). Lastly, COVID-19-induced lockdowns in various countries have been witnessed to lead to a major decline in COVID-19 spread. Strict lockdowns directly decreased inter-individual physical contacts and cut down the transmission route for COVID-19. Lockdown policies aiming to reduce contacts in large groups, such as canceling public events, imposing restrictions on private gatherings and closing schools and workplaces, were the most effective interventions for COVID-19 outbreaks (Askitas et al., 2021). In European countries, the lockdown policy made a great contribution to the decline in SARS-CoV-2 transmission (Flaxman et al., 2020). Besides, the lockdown policy led to travel restrictions, which contained the spread of COVID-19 to other places or cities. For example, in China, after the lockdown on January 23, the population migration flow witnessed a dramatic decline, which successfully mitigated the number of COVID-19 cases and its growth in China's provinces (Kraemer et al., 2020). This may explain why the relationship between human migration and COVID-19 incidence became weaker after the lockdown (Qiu et al., 2020; Wu et al., 2021).

2.1.6. *Socioeconomic factors*

Socioeconomic factors are considered as crucial variables for measuring the vulnerability of groups to COVID-19. Previous studies in different countries indicated that income or its inequality as a social background is an influential factor in COVID-19 incidence (Calderon-Larranaga et al., 2020). For example, a study from Colombia found that the Poverty index, for which a higher index indicates higher socioeconomic deprivation, is a major factor in COVID-19 mortality in developing countries (Rodriguez-Villamizar et al., 2020). Some socio-economic indicators such as GDP, income and trade-related factors can also be used to explain the spread of COVID-19. A worldwide study found that GDP is one of the most significant factors impacting COVID-19 fatalities (Chakraborti et al., 2020). Per capita GDP shows a positive impact on COVID-19 incidence. In city-level or nationwide research, some developing countries such as China exhibited a negative correlation between COVID-19 incidence and per capita GDP (Qiu et al., 2020; Wu et al., 2021). Lower income has placed a heavy burden on countries trying to effectively stop the COVID-19 pandemic; thus, some studies have focused on how low-income countries prevent COVID-19 outbreaks (Adelodun et al., 2020; Donde et al., 2021). Moreover, government income support programs have globally avoided 3.6 million COVID-19 cases and 166,690 deaths (Asfaw, 2021). Some trade-related factors further explain the spread of COVID-19, as they require closer social communication in some geo-economic areas (Bontempi et al., 2021). Total imports and exports, as a commercial trade-related factor, was used to interpret COVID-19 transmission dynamics (Bontempi et al., 2021). It is a complex variable reflected by human activities, such as population density, economic dynamism and human mobility (Bontempi et al., 2021). Bontempi and Coccia underlined its high correlation with COVID-19 confirmed cases, over 78%, and demonstrated how it can be used in epidemiological model development (Bontempi and Coccia, 2021).

2.1.7. *Comorbidity*

Comorbidities have impacts on COVID-19 outcomes. A worldwide study using online-based self-reported data indicates that higher risks of COVID-19 are observed in patients of the same gender and age with any of various exiting comorbidities, which are liver, kidney, heart, and lung disease, and diabetes (Alam et al., 2021). In England, people with chronic kidney disease/obesity are more likely to contract SARS-CoV-2 (de Lusignan et al., 2020). In Colombia, the prevalence of hypertension, over 6%, contributed to the number of COVID-19 deaths (Rodriguez-Villamizar et al., 2020). Pre-existing diseases, such as cardiovascular disease, coronary artery disease and arrhythmia, were also commonly seen in COVID-19 patients in Georgia, USA (Gold et al., 2020).

2.2. *Interactive effect of environment on COVID-19*

Generally, COVID-19 transmission is affected by multiple environmental factors. On the one hand, some natural factors, especially meteorological factors and air pollution, have a profound correlation with other natural factors within the natural system; as do certain human factors in human society. On the other hand, the natural and human environments interact with each other, and their influence on COVID-19 incidence is complicated. In short, their interactions should be incorporated into models of impacts on COVID-19. **Fig. 5** shows the interactive effects of natural and human factors on COVID-19.

2.2.1. *Interaction of natural factors*

Climatic conditions are important for COVID-19 incidence, and most meteorological factors, such as H, wind speed and precipitation, interact with T to affect the transmission of COVID-19 from a microscopic viewpoint, which indicates the survival of SARS-CoV-2 in different climatic conditions. A worldwide study suggests that from November 2019 to January 2020, countries with unfavorable climatic suitability for SARS-CoV-2, such as Canada, Australia and Malaysia, had the slowest increase in COVID-19 cases, while regions located in the subtropical belt of combined UV radiation-air T-Rh were the most suitable for SARS-CoV-2 (Sfîcă et al., 2020). Warm T and the lack of UV radiation in mild and humid winters provide optimal conditions for COVID-19 transmission and for the virus to develop in different countries and cities (Sfîcă et al., 2020). Moreover, the interactions of meteorological factors are correlated with COVID-19 incidence. In six South Asian countries, T, air pressure, and H significantly impacted the numbers of COVID-19 confirmed cases (Jain et al., 2021). In Bangladesh, as the summer and rainy seasons came, the COVID-19 transmission was effectively reduced (Xie and Zhu, 2020). The interaction of these factors was extensively observed in China. Local weather conditions with low T, mild diurnal T range and low H likely favored COVID-19 transmission (Liu et al., 2020b). A study showed that the Rh and Ave T in Hubei province had a combined impact on COVID-19 incidence. In the range of Ave T between 5.04°C and 8.2°C, every 1% increase in Rh led to a decrease in daily confirmed cases of 11% to 22%, while for average Rh in the range of 67% to 85.5%, every 1°C rise in Ave T was associated with a decrease in daily confirmed cases by 36% to 57% (Qi et al., 2020). Another study showed that low T and moderate precipitation increased the risk of

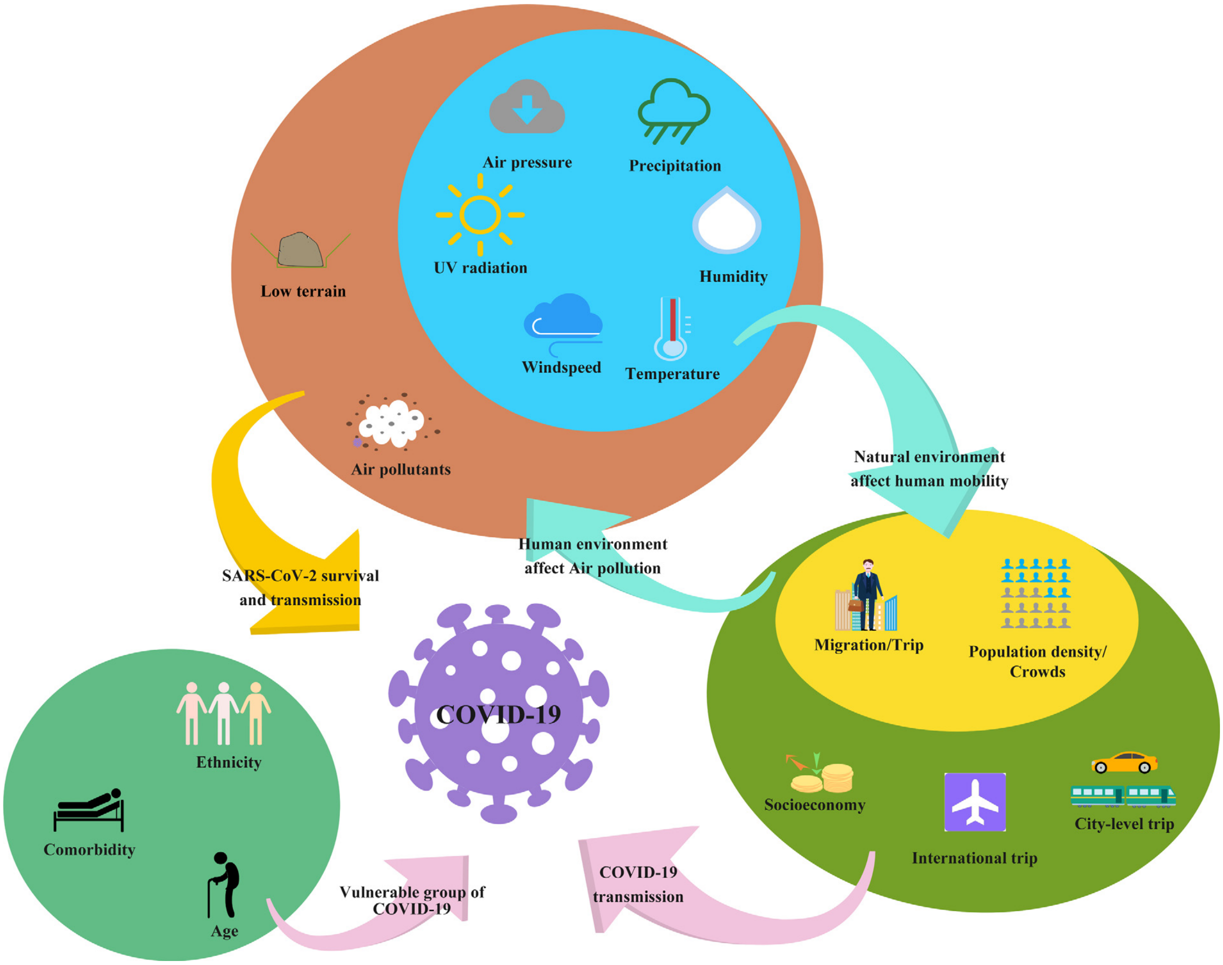

Fig. 5 – Interactive effects of natural and human environmental factors on COVID-19 incidence.

COVID-19 (Wei et al., 2020). With increasing wind speed, warm areas were more likely to be threatened by COVID-19 spread (Wei et al., 2020).

Meteorological factors and air quality together impact the COVID-19 incidence and the survival time of the coronavirus on the micro-scale. Air T and Rh have been proven to contribute to SARS-CoV-2 spread and survival time by affecting the evaporation of droplets that carry SARS-CoV-2 (Zarei et al., 2021). A study in Dhaka City, Bangladesh indicated a correlation between meteorological factors and air quality parameters, suggesting that the nexus between these two had an impact on COVID-19 cases (Rahman et al., 2020). In China, low Rh enhanced the impact of the Air Quality Index (AQI) on the COVID-19 spread (Xu et al., 2020a). Air pollution had a stronger impact on COVID-19 incidence when the T was 10-20°C or Rh 10-20% (Xu et al., 2020a). In winter, the atmosphere is quite stable, and because of the low terrain in Hubei province, it is hard for air pollution to spread out, leading to a decrease in the solar radiation; thus, the virus is more active, causing a higher risk of COVID-19 incidence (Sfîcă et al., 2020). Moreover, SARS-CoV-2 is airborne and can survive stably when attached to aerosols (van Doremalen et al., 2020), while low wind speed decreases air circulation, leading to stagnation of air pollution with SARS-CoV-2, especially in fall and winter (Coccia, 2021b). Thus, lower wind speed may cause a higher density of infectious droplets and more transmission (Hossain et al., 2020). In Italy, a greater number of COVID-19 infected cases were found more likely to occur in cities bordering megacities where the wind speed is low and frequently suffer from high air pollution (Coccia, 2021a, 2021b, 2021c). In China, a study indicated that higher wind speed cleans the air and decreases the concentrations of small particles containing the virus, which limits the spread (Qiu et al., 2020). Besides, both wind speed and air pressure increase SARS-CoV-2 transmission by accelerating the droplets the virus attaches to (Sarkodie and Owusu, 2020). Another meteorological factor that can interact with air pollution is precipitation. Because of the accumulation and washout process of aerosols and microbial bio-aerosols on rainy days, the viruses could not be suspended for long times in the atmosphere (Hossain et al., 2020).

2.2.2. *Interaction of natural and human factors*

Meteorological factors and human mobility together increase the transmission of COVID-19, which indicates the interactions on the macro-scale affecting human behavior. People are more likely to gather and move outside in warm conditions, which promotes the spread and survival of the virus (Sfîcă et al., 2020), and another globe-level study verified the positive association between T and walking mobility; at the same time, the correlation between walking mobility and the COVID-19 transmission rate is also positive (Shao et al., 2021). A study in China indicated that environmental factors and population density together influence the COVID-19 transmission rate, since the weather conditions may have a positive impact on human social activities (Qiu et al., 2020). In south Asian countries, rainy days increase the probability of people staying at home, which reduces COVID-19 transmission (Hossain et al., 2020). A study indicated that mean T and precipitation can respectively interact with the proportion of population flow from Wuhan before/after Wuhan's lockdown, and the effects of their interactions on COVID-19 transmission are positive and negative (Wu et al., 2021). A worldwide study explained that morning is the most humid time of day, and it is also the time when most people commute, providing the best conditions for transmission of the coronavirus (Sfîcă et al., 2020). A study comparing Japan, China, England and Germany argued that absolute H, T and population density are cofactors impacting the COVID-19 pandemic durations in the spread and decay stage, although the lockdown policy can weaken their effect (Diao et al., 2021). Besides, cities in countries with lockdown measures showed heterogeneous effects, where those with a lower income level and larger population were more effective in reducing air pollution, leading to less COVID-19 incidence in the same period (Liu et al., 2020a).

2.2.3. Interaction of human factors

Human factors have complex interactions, with profound consequences for COVID-19 transmission. Firstly, some human factors interact leading to easier contact with COVID-19. In China, a study showed that higher migration scale and more crowding of travelers within one city together increased the possibility of disease outbreak (Wu et al., 2021). In Brazil, people with high income were more likely to be able to afford a costly international trip to countries like Italy at the beginning of COVID-19, leading to higher infection rates in high-income areas (de Magalhaes et al., 2020). However, a study in Texas suggested that people with higher income have less outdoor mobility than lower-income individuals, thus they have a lower rate of contracting the coronavirus (Iio et al., 2021). Secondly, the physical condition of people, combining the interactions of age, race and comorbidity, is crucial for identifying COVID-19 vulnerable groups (Calderon-Larranaga et al., 2020). A worldwide study showed that advanced age and comorbidity together explain COVID-19-related deaths (Polidori et al., 2021). Moreover, a study in the US indicated that more Black people have comorbidities, such as obesity and diabetes, at younger age, leading to worse COVID-19 hospitalization outcomes (Munoz-Price et al., 2020). In the US, differences in chronic health conditions, low socioeconomic status or lack of economic stability caused racial disparities in exposure to SARS-CoV-2 during the COVID-19 epidemic (Saini et al., 2021). Thirdly, socioeconomic factors and human mobility are closely related in international trade, which can explain the long-distance transmission of SARS-CoV-2. Compared with the single factor of human mobility for traveling during the COVID-19 pandemic, commercial relationships are based on globally persistent mobility patterns and personal social interactions (Bontempi, 2020). To better describe the transmission dynamics of COVID-19 within and between countries, Bontempi proposed a comprehensive indicator reflected by population density, the sum of the value of import and export, GDP and human mobility. The result showed that regions with higher levels of international trade activity, representing living standards, economic dynamics and globalization, are more likely to come in contact with foreign populations, corresponding to increased risk of SARS-CoV-2 importation and transmission in their communities (Bontempi et al., 2021).

2.3. *Impact of COVID-19 induced lockdown on environment*

2.3.1. Impact on air pollution

COVID-19-induced lockdowns led to improvements in air quality. As a result of long-term and large-scale lockdown policies for controlling COVID-19 spread, most air pollutants in many countries and regions decreased (Liu et al., 2020a). For example, in 44 cities of China, the dramatic reduction in air pollution emissions resulted from travel restrictions for the control of COVID-19, and the AQI decreased by 7.8% on average (Bao and Zhang, 2020).

The concentrations of different pollutants experienced varying responses to the COVID-19 lockdowns. **Fig. 4** shows the changes in different air pollutants resulting from COVID-19 induced lockdowns. A decreasing trend was seen in the concentrations of NO_x, PM, SO_2, and CO_x, while the O_3 level saw a rise. The rise in O_3 is explained by the decrease in the NO_2 average concentration, which reduces the level of NO, leading to constraints on the NO+O_3 reaction (Xu et al., 2020b). The COVID-19 pandemic caused a remarkable fall in NO_x concentrations, which was one of the most prominent side effects of social lockdown (Liu et al., 2020a). Globally, the NO_2 AQI value fell the most among all the pollutants compared with pre-lockdown levels (23%-37%) (Liu et al., 2020a). An observation on levels of NO_x in China illustrated a reduction of 36%, resulting from the restrictions on transportation (Feng et al., 2020). During the COVID-19 epidemic, NO_2 emissions dropped significantly due to the shutdowns in China, India, Italy, and the US (Paital, 2020). More specific studies showed that during the lockdown the NO_2 concentration decreased in California (Liu et al., 2020c) and some cities in China (Shi and Brasseur, 2020) by 38% and 60%, respectively. Moreover, due to COVID-19 mitigation strategies, like the shutdown, the fluctuations in NO_x concentrations revealed a spatial pattern. During the COVID-19 pandemic in China, NO_x has seen a dramatic fall in major cities (Shi and Brasseur, 2020). A study in California, US observed that NO_2 concentrations over major powerplants showed a decreasing trend and clearly dropped over transportation hubs/residential complexes near the national highways during the whole period of the COVID-19 lockdown (Liu et al., 2020c). The improvements in PM, like PM_{10} and $PM_{2.5}$, have been mentioned many times to support the benefits of COVID-19 restrictions. The decline in PM concentrations is clearly due to the restriction on transportation and the economy during the quarantine. As for PM_{10}, it has shown a decline during COVID-19 lockdowns. A study detecting daily PM_{10} concentrations globally showed that it fell by 14%-20% in locked-down cities (Liu et al., 2020a). Evidence in Chinese cities showed that reductions in human mobility caused a 13.66% PM_{10} drop (Bao and Zhang, 2020). The concentration of $PM_{2.5}$ also decreased during the COVID-19 pandemic in many countries and cities. Compared with pre-lockdown, $PM_{2.5}$ exhibited a worldwide decline of 7-16% (Liu et al., 2020a). A study in China showed that the $PM_{2.5}$ concentration during the restriction fell almost 35% on average (Shi and Brasseur, 2020), while in northern cities it dropped by 5.93% (Bao and Zhang, 2020). The drop in California was slight, compared with other air pollutants like CO and NO_2 (Liu et al., 2020c). However, in contrast to the evidence above, in regions including North China, East China and especially in Hubei province in Central China, several fine PM pollution episodes still occurred despite the strict lockdown policy in these regions (Le et al., 2020; Shen et al., 2021). Meteorological factors had an impact on the anomalies that occurred during the COVID-19 lockdown period Shen et al., 2021. argued that in observations of six $PM_{2.5}$ pollution episodes in Hubei province, air pressure, wind speed and long-scale transmission of $PM_{2.5}$ were the main factors. These factors cause two types of $PM_{2.5}$ accumulation. One is long-term transmission from other regions due to strong wind speed and air pressure gradients, the other is $PM_{2.5}$ accumulation near the surface resulting from low windspeed and uniform air pressure.

Due to the shutdown of factories and the decline in exhaust emissions, SO_2 concentrations fell. The global concentration of SO_2 decreased by 2%-20% during the lockdown (Liu et al., 2020a). The average SO_2 concentrations decreased by 6.76% in 44 cities in China (Bao and Zhang, 2020). A reduction in carbon emissions could also be observed during the COVID-19 period. A worldwide study showed that CO dropped by 7-11% during COVID-19 (Liu et al., 2020a). A city-level study showed a reduction in CO concentrations of 4.58% during the period of travel restriction in China due to COVID-19 (Bao and Zhang, 2020). A similar drop could be seen in California (Liu et al., 2020c). CO_2 emissions in countries like China, Italy, UK and Germany were dramatically reduced to $<40\%$ of pre-pandemic levels or lower due to the restrictions on cars and fossil fuels during the COVID-19 pandemic (Paital, 2020). Different from the above pollutants, the COVID-19 shutdown led to a rise in ozone levels. A study compared the global O_3 individual AQI before and after the lockdown, indicating that the concentration of O_3 increased by 10%-27% (Liu et al., 2020a). The O_3 level in China increased significantly due to the restrictions on the economy, like factory shutdowns (Shi and Brasseur, 2020).

2.3.2. *Impact on the ecological environment (wildlife)*

The unprecedented worldwide lockdown to control COVID-19 spread has had an obvious impact on wildlife. Firstly, because of the lockdown, more wild species were observed by people in places where they had not been seen before (Rutz et al., 2020). In particular, wild animals were found to be moving across roads, cities, and other human habitations (Paital, 2020). In Italy, without fear generated by human activities, mammals and birds appeared in urban areas (Manenti et al., 2020). Secondly, during the lockdown, some wildlife may have changed their living habits. Some nocturnal or crepuscular species, like the Eastern cottontail *Sylvilagus floridanus*, could be seen frequently during the daytime in Italy. Evidence of changes in animal and bird breeding and nest distribution was also provided (Manenti et al., 2020). Thirdly, COVID-19, to some extent, threatened animals' lives. The lives of some urban citizens and endangered animals were under increasing pressure because of the large-scale shifts in human activities as well as the re-emergence of some endangered animals (Barouki et al., 2021; Rutz et al., 2020). Wildlife and endangered species face the highest risk of COVID-19 infection (Damas et al., 2020).

2.3.3. *Impact on the socio-economy*

The COVID-19 pandemic has caused a global recession. According to *Global Economic Prospects, June 2020*, COVID-19 triggered the deepest global recession in eight decades, with a 5.2% shrinkage in global GDP in 2020 (Arteta et al., 2020). COVID-19-induced containment strategies delivered huge economic losses (Guan et al., 2020). For example, in China, controlling and preventing the COVID-19 outbreak caused a heavy economic burden on the government (Jin et al., 2021). In Italy, the lockdown policy reduced almost all commercial activities because of the restrictions on human mobility (Bontempi and Coccia, 2021). In New Zealand and Australia, the COVID-19 lockdown led to a decline in specialized and non-specialized labor availability, which had an impact on the supply chain and market (Perracini et al., 2021).

3. Discussion

3.1. *Future research perspectives*

The relationship between the environment and COVID-19 spread has been revealed in previous studies. However, as the worldwide spread of COVID-19 has become increasingly intense, the main challenges are avoiding large-scale outbreaks and facing new situations. Thus, in this section, we also give some recommendations for future research based on these two aspects (**Table 2**).

Regarding the impact of the environment on COVID-19 incidence, three themes need focused attention. Firstly, it is important to note that climate change-induced disasters, such as wildfire, have caused an undeniable knock-on effect on COVID-19 spread. Climate change has been a key factor in wildfire occurrence (Fasullo et al., 2018). Solid evidence in the US proved that wildfire has amplified the effect of short-term $PM_{2.5}$ exposure on COVID-19 transmission due to massive smoke pollution, regardless of some heterogeneity across counties (Zhou et al., 2021). As the season of wildfire approaches, the interaction between SARS-CoV-2 and wildfire smoke calls for much more attention (Henderson, 2020). Secondly, it is necessary to determine the thresholds of main air pollutants for preventing and controlling COVID-19 spread at a finer spatial scale, such as at the city level. Changes in air pollutant concentrations have been observed during the COVID-19 lockdown. Some studies have reported on the determination of threshold $PM_{2.5}$ concentrations in various countries (Liu et al., 2021). Apart from fine particulate matter ($PM_{2.5}$), nitrogen dioxide (NO_2) also increases the COVID-19 infection rate and severity; thus, its emission needs to be controlled (Paital and Agrawal, 2020). Long-term exposure to higher NO_2 concentrations was found to be positively related

Table 2 – Further research perspectives related to COVID-19 and environment interactions.

Future research perspective	
Environment-COVID-19	1. Paying more attention to the effect of climate change-induced disasters such as wildfire on COVID-19 spread, so that policymakers can evaluate the risks and take corresponding action immediately. 2. Determining thresholds of main air pollutants including NO_2 concentration for preventing and controlling COVID-19 spread at finer spatial scale, such as at the city level. 3. Investigations on COVID-19 transmission in more potential sources such as wastewater.
COVID-19-environment	1. COVID-19 lockdown has effects on the weather system, which has led to some atmospheric events, such as abnormal precipitation and lightning. 2. COVID-19 lockdown causes more frequent appearance of wildlife in human living areas, thus increasing the risk of the occurrence and prevalence of some zoonoses.

to the COVID-19 case-fatality rate and mortality rate in the US and England (Konstantinoudis et al., 2021; Liang et al., 2020). However, man-made emissions of NO_2 cannot be completely banned at present; thus, research on determining thresholds at the city level is still needed. Thirdly, there is a need to investigate more potential sources of COVID-19 transmission. Many research studies and reviews have suggested that SARS-CoV-2 and its RNA can be detected in wastewater, although its effect on humans is not yet been confirmed (Sharma et al., 2021; Rahimi et al., 2021). There are still many possibilities for activating SARS-CoV-2 in the process of wastewater treatment, such as mutation, changing water T or PH levels, which has increased the level of uncertainty in COVID-19 prevention (Rahimi et al., 2021).

For the impact of COVID-19 lockdowns on the environment, two themes need further research attention. Firstly, the effects of COVID-19 lockdowns on the weather system need more concern as they have led to some atmospheric events. For instance, the reduction in observed Asian aerosol loadings caused by COVID-19-induced lockdown measures changed atmospheric circulation, which increased rainfall in India (Fadnavis et al., 2021). Because of the reduction in air pollutants during the COVID-19 lockdown, a considerable decrease in lightning activities over the Kolkata megacity in India was observed (Chowdhuri et al., 2020). Secondly, COVID-19 lockdowns caused more frequent appearance of wildlife in human living areas, thus increasing the risk of the occurrence and prevalence of some zoonoses. The increased range of wildlife increases their opportunity to come in contact with humans. The fact that SARS-CoV-2 has the potential for cross-species transmission among animals has been frequently discussed (Swelum et al., 2020). A previous study found that the whole genome sequence of a bat SARS-related coronavirus (SARSr-CoV; RaTG13) collected in Yunnan province, China has 96.2% similarity with 2019-nCoV (Zhou et al., 2020). The two major lineages (L and S lineages) of SARS-CoV-2 viruses are well defined by two single nucleotide polymorphisms, showing complete linkage across SARS-CoV-2 strains, with the S lineage appearing to be more related to coronaviruses in animals (Tang et al., 2020). Moreover, other zoonoses may seriously threaten human health and survival. Previous studies have warned that zoonoses widely exist in ecological environments, and the rise of emerging infectious diseases spreading between humans and animals has threatened human welfare (Karesh et al., 2005; Taylor et al., 2001). Hence, it is becoming increasingly important to prevent humans from frequent contact with wildlife.

3.2. *Future adaptation strategies*

Adaptation to the COVID-19 pandemic involves more comprehensive knowledge. The critical decision-making for preventing outbreaks should reduce uncertainties and provide proactive and recovery strategies (Coccia, 2021e). The strategies for COVID-19 prevention should focus on facing problems such as vaccination, health expenditures, and maintaining a sustainable environment.

3.2.1. *Strategies for sustainable environment*

The ongoing COVID-19 pandemic has caused great concern for the need for a sustainable environment (Coccia, 2020b; Coccia, 2021g, 2021h). Choosing more sustainable actions is challenging for future protection from COVID-19. Future strategies in this field to adapt to recurring COVID-19 outbreaks should focus on two aspects. One is the demand for cleaner energy and technologies. The lockdown immensely improved air quality by reducing public transportation and industrial production, but exposure to a polluted environment and greenhouse gas emissions has caused more COVID-19 cases and mortality and created a favorable propagation environment for the virus (Srivastava, 2021; Kumar et al., 2022). Industrial pollution has been proven to trigger the mechanism of air pollution-to-human transmission dynamics of COVID-19 (Coccia, 2020b). Coccia highlights the high transmission of COVID-19 in Italian cities with a higher level of air pollution and lower wind speed/low T (Coccia, 2021a, 2021b). In Northern Italian cities, less wind energy production and high air pollution have caused greater numbers of COVID-19 cases and deaths. By contrast, cities in the south with high production of wind energy and low air pollution have led to a cleaner environment and better air quality, suffering from less COVID-19 related mortality, although the windspeed is high (Coccia, 2020c). Moreover, a major concern worldwide is the elevation of CO_2 emission levels from recovering economies after the strict lockdown policy (Kumar et al., 2022). Thus, the development of renewable energy plays an important and positive role in future adaptability. The other is to cope with the environmental consequences of using personal protective equipment (PPE) against the COVID-19 pandemic. Due to the avenue of SARS-CoV-2 propagation, PPEs, such as face masks, gloves and face protectors, are strongly recommended for individuals (Facciolà et al., 2021). However, the disposal of used PPEs, which are a potential source of micro- and nanoplastics, has resulted in environmental hazards (Kutralam-Muniasamy et al., 2022). The wastes have polluted freshwater and marine ecosystems, and can be easily ingested by higher organisms via entering the food chain (Facciolà et al., 2021). Therefore, the potential for chronic health problems for humans and animals has raised awareness of this problem. Urgent sustainable actions should be chosen. The plastic material of PPEs should be replaced by sustainable alternatives, such as biobased plastics; the waste management streams should be improved and priority given to flexible and decentralized approaches; and the general public, stakeholders, industries should pay greater attention to and be responsible for the waste and related environmental pollution management (Patrício Silva et al., 2021).

3.2.2. *Strategies for public policy*

In order to control the COVID-19 pandemic, all countries have taken adaptive measures in response. Social lockdown is the most effective human intervention in the early stages of COVID-19 transmission compared with other measures, especially in countries with a large population and poor medical systems. More importantly, in these countries, especially India, social lockdown has greatly improved air and water quality (Paital et al., 2020). However, long-term lockdowns will seriously damage economic growth and trigger an economic crisis, and will not significantly reduce the COVID-19 fatality rate (Coccia, 2021d). Moreover, the home environment is able to pose a threat to further COVID-19 outbreaks, and reducing indoor transmission will benefit COVID-19 prevention and control (Tang et al., 2022). Thus, a public policy response is needed to cope with the negative effects of recurring waves of COVID-19 on human health (Coccia, 2021f; Núñez-Delgado et al., 2021). For future adaptation, more effective and flexible strategies should be considered rather than short-term lockdowns (Coccia, 2021g).

Faced with the sequential waves of the COVID-19 outbreak, strategies should also focus on an effective response policy to provide concrete measures in the long run. The focus of these policies should be on how to better deal with the negative impact of future pandemics, especially on public health and the economy. A study in Italy comparing the first and second waves of the COVID-19 pandemic indicated a more stationary trend of COVID-19 incidence and a lower negative impact in society in the second wave of COVID-19 pandemic than the first wave. This calls for absorbing lessons from the past waves and policy responses for containment of the COVID-19 pandemic (Coccia, 2021f). Coccia highlights the fact that European countries with ambiguous, delayed and uncertain policy responses showed a low capability for coping with COVID-19 pandemic negative effects. More than that, all countries in Europe still need to reinforce their barriers against the pandemic, because high preparedness for full prevention is not yet enough (Coccia, 2021f; Coccia, 2022). Timely assessment of the resilience and preparedness of countries could provide a reference for decision-making, and for the COVID-19 pandemic, the goal of which is to minimize mortality and maximize vaccination (Coccia, 2022). At present, vaccination has become an appealing technical solution for preventing the public from the unforeseen COVID-19 pandemic. However, the main point is how to make vaccination a priority not only for the government but for public health. Manifold factors can affect vaccination programs. On the one hand, the level of public trust in COVID-19 vaccination still calls for more attention. Vaccination confidence could be a better indicator for the improvement of the public health system. Vaccination hesitancy is still a problem, although different types of vaccines have been developed (Harrison and Wu, 2020; Zarei et al., 2021). On the other hand, sufficient financial support for the health sector is becoming increasingly important for successive COVID-19 waves. Statistical evidence from more than 160 countries suggests that countries with lower fatality rates have a high average level of health expenditure (7.6%) relative to GDP and average government health expenditure per capita of about $2,300, while those with higher fatality rates have a lower investment in the healthcare sector (Coccia, 2021g). Nana-Sinkam suggests that solutions for addressing health disparities and inequalities during the COVID-19 pandemic will require increased financial support. The growing demand for telehealth, experienced community health workers and the distribution of vaccines, particularly among higher-risk individuals, reveals the need for more healthcare investment (Nana-Sinkam et al., 2021).

4. Conclusions

In conclusion, COVID-19 is still prevalent in many countries around the world and will not be eliminated within a short time. In this review, we performed a review of 100 papers on the associations among COVID-19, the natural and human environments at varying scales (including global, country and city-level). On the one hand, the COVID-19 pandemic, natural and human environments are vitally interrelated, even though some spatial heterogeneity and uncertainty exist. Also, the interactions of environment factors are able to better explain the dynamics of COVID-19 transmission. The natural environment can not only affect the survival of SARS-CoV-2 in the environment but also that of individuals by impacting human mobility and behaviors. For another, the COVID-19-induced lockdowns caused air pollution reduction, wildlife shifts and socio-economic depression. Further, we give recommendations both on future research and adaptation strategies for the COVID-19 pandemic and environment interactions. Future research should be extended to both the effects of the environment on the COVID-19 pandemic and COVID-19-induced change on the environment. The impact of climate change-induced disasters, determining safe thresholds of main air pollutants at a finer spatial scale and other potential sources (such as wastewater) aggravating the COVID-19 pandemic still call for more attention. Also, the impact of COVID-19-induced changes, such as atmospheric events and the spread of wildlife-induced zoonoses, need for more awareness. In addition, we suggest that future adaptation strategies should focus on maintaining a sustainable environment and on public policy response. Strategies for a sustainable environment mainly include demand for cleaner energy and technologies and coping with discarded PPEs. The public policy response should also manage to reduce the negative effects of consequential COVID-19 outbreaks by maximizing vaccination and providing more investment in the health sector.

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Appendix A Supplementary data

Supplementary material associated with this article can be found, in the online version, at doi:10.1016/j.jes.2022.02.016.

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