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COVID-19 and the environment: A critical review and research agenda

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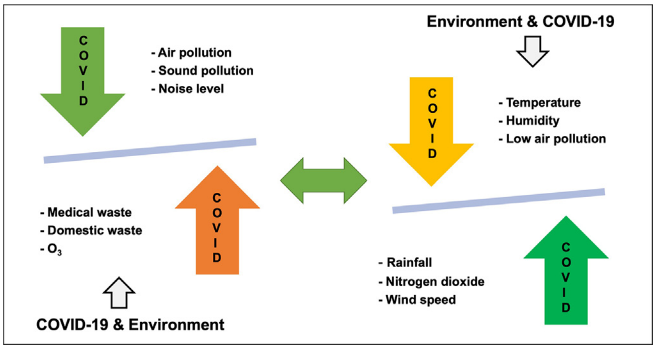
HIGHLIGHTS

- A critical yet comprehensive review of studies on COVID-19 and the environment
- Environmental factors have significant effect on COVID-19 transmission, and vice-versa.
- Critical reflection on methodologies used in existing studies.

GRAPHICAL ABSTRACT



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ABSTRACT

The current Coronavirus infection (COVID-19) outbreak has had a substantial impact on many aspects of general life. Although a number of studies have been published on the topic already, there has not been a critical review of studies on the impacts of COVID-19 by and on environmental factors. The current study fills this gap by presenting a critical analysis of 57 studies on the nexus between COVID-19 and the environment, published in nine journals up to May 2020. Majority of the studies in our sample are published in *Science of the Total Environment* (74%), and studies used mostly descriptive statistics and regression as research methods. We identified four underlying research clusters based on a systematic content analysis of the studies. The clusters are: (1) COVID-19 and environmental degradation, (2) COVID-19 and air pollution, (3) COVID-19 and climate/metrological factors and (4) COVID-19 and temperature. Besides a critical analysis of the studies in each cluster, we propose research questions to guide future research on the relationship between COVID-19 and the environment.

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1. Introduction

Coronavirus disease (COVID-19) is spreading globally, which is not merely a health problem, but also affects the world economy and the environment in diverse ways. As of July 10, 2020, 12.10 million people have been affected worldwide and 551,046 have died (WHO, 2020). While COVID-19 is causing severe damage to economies and societies, it has augmented the environment as pollution has reduced significantly (Chakraborty and Maity, 2020). Due to COVID-19, governments have imposed restrictions on the movement of people, vehicles, and suspended industrial activities (Zambrano-Monserrate et al., 2020). The consequences of such lockdowns have been remarkable, as pollution levels have dropped significantly; for instance, greenhouse gas emissions, nitrogen dioxide, black carbon and water pollution have decreased drastically (Chakraborty and Maity, 2020; Saadat et al., 2020; Tobías et al., 2020; Wang and Su, 2020; Zambrano-Monserrate et al., 2020).

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In Barcelona, Spain, for example, air pollution levels dropped by 50% during the lockdown period, notably, nitrogen dioxide (NO_2) and black carbon (BC) rates declined by 45–51% (Tobías et al., 2020). However, ozone (O_3) levels in Barcelona increased by between 33% and 57% during the lockdown period (Tobías et al., 2020). In China, carbon emissions dropped by 25% during lockdown, that is, approximately 1 million tons less compared to same period last year (Wang and Su, 2020). In Malaysia, particulate matter ($PM_{2.5}$) dropped by approximately 58.4% during that country's lockdown (Abdullah et al., 2020). Water pollution in Venice, Italy was significantly reduced due to lockdown as a result water canals of Venice became more transparent compared to the pre-lockdown period (Saadat et al., 2020). Likewise, the surface water quality in the Vembanad Lake in India improved significantly during that country's lockdown period as suspended particulate matter (SPM) dropped by 15.9% compared to the pre-lockdown phase (Yunus et al., 2020). Meanwhile, COVID-19 is also having adverse consequences on the environment due to the hefty amount of domestic and medical litter and the lack of initiatives to recycle medical trash in fear of the surge to spread COVID-19 to the people associated with recycling (Zambrano-Monserrate et al., 2020).

While the pros and cons of COVID-19 on the environment are evident in the literature, the environment or climate has also had a significant influence on COVID-19 transmissions and mortality. Several studies have reported a significant correlation between climate indicators such as temperature, due point, humidity, wind speed, rainfall and COVID-19 transmissions and fatality (Ma et al., 2020; Pirouz et al., 2020; Qi et al., 2020; Şahin, 2020; Sobral et al., 2020; Zhu et al., 2020). Moreover, studies have argued that temperature influences the COVID-19 transmissions, but have found mixed (positive, negative and insignificant) impacts on COVID-19 transmissions (Briz-Redón and Serrano-Aroca, 2020; Prata et al., 2020; Shi et al., 2020; Xie and Zhu, 2020). Air pollution is another crucial indicator that affects the COVID-19 transmission and mortality rate (Abdullah et al., 2020; Carrington, 2020; Muhammad et al., 2020). Northern Italy, where the air is more polluted than the rest of the country, was struck relatively hard by COVID-19, with significantly higher incidence and related casualties (Carrington, 2020). Therefore, COVID-19 can influence the environmental factors and vice versa. While investigating this phenomenon, most studies have focused on one side of the coin or the other. However, to the best of our knowledge, no studies have explored the bidirectional characteristics of COVID-19 and the environment. Being an emerging study domain, a critical review of studies on the nexus between the COVID-19 and the environment can formulate a current state of knowledge that could provide directions to future research. Furthermore, such a review can summarize methodological advancement, which can be implemented in the context of countries other than the studied ones to further investigate the relationship between COVID-19 and the environmental.

2. Research methodology

The first step is to extract articles on the topic of interest: COVID-19 and the environment. We searched in the Scopus database – one of the largest academic literature databases, with more than 69 million indexed documents – using a combination of keywords as shown in Table 1. The initial keyword search on May 2, 2020 retrieved 859 studies. After limiting language to "English" and document type to "Article", 462 articles were left for analysis. To ensure relevance to COVID-19 and the environment, we manually screened 462 by title, keywords, abstract and, when unsure, by assessing the full text. Finally, excluding studies focusing on earlier coronaviruses (such as MERS-CoV and SARS-CoV) or only COVID-19 (without environment), 57 studies were found relevant and selected for further analysis.

Table 1
Keyword search.

No.	Keyword search (May 2, 2020)	#Articles
1	("Coronavirus disease 2019" OR "COVID-19" OR "Novel Coronavirus" OR "Sars-Cov-2") AND ("environment" OR "climate" OR "weather" OR "pollution" OR "environment* pollution")	859
2	Refined By: Languages: (English)	826
3	Limit to Article	462
4	Manually screened	57

All of the selected articles were studied thoroughly and revealed four underlying research clusters. For this purpose, we formed a concept matrix in Microsoft Excel with article title, year, authors, journal, keywords, purpose, data source, sample country, methodology, theme and main findings. The themes of studies were coded manually while analysing the full texts. Following an iterative theme coding process, we concluded that the sample of 57 studies can be categorised into four research clusters. We then analysed the studies in each cluster in detail for critical reflection and proposed future research questions.

3. Results

The interrelationship between COVID-19 and the environment is an emerging research topic. Based on an in-depth review of the content of 57 studies, we identified four research clusters: (1) COVID-19 and the environmental degradation, (2) COVID-19 and air pollution, (3) COVID-19 and climate/metrological factors and (4) COVID-19 and temperature. A comprehensive reflection of the studies on each cluster is presented in Table 2.

3.1. COVID-19 and environmental degradation

While the COVID-19 pandemic has had an unprecedented effect on society and the economy, to the contrary, it has helped repair some environmental damage (Chakraborty and Maity, 2020). Greenhouse gas emissions (GHG), nitrogen dioxide (NO_2), water pollution, noise pollution and pollution in beaches have reduced significantly due to full or partial lockdowns and strict movement control order (MCO) by many governments across the world (Chakraborty and Maity, 2020; Saadat et al., 2020; Wang and Su, 2020; Zambrano-Monserrate et al., 2020). Such restrictions have helped countries reduce their environmental pollution and improve air quality and quality of life (Chakraborty and Maity, 2020). However, the findings do not support the reduction of GHG in the long run because, after the removal of lockdown, the economic activities and energy consumption are likely to return to normal as large-scale industrial activities will be resumed, which will result in more energy consumption and GHG emissions, and likely outstrip the limit during the lockdown period (Wang and Su, 2020).

Moreover, Zambrano-Monserrate et al. (2020) described the indirect effect of lockdown on the environment, indicating that it reduced sound pollution and the pollution in beaches and improved air quality. Sound pollution was caused by extensive industrial activities and harmed public health and damage natural ecosystems (Zambrano-Monserrate and Ruano, 2019). Lockdown restricted the movement of public transport and halted industrial activities completely, resulting in a significant reduction of noise pollution worldwide (Zambrano-Monserrate and Ruano, 2019). Likewise, pollution in beaches in places including Acapulco, Barcelona and Salinas reduced drastically, and the water has become clear due to low numbers of tourists (Zambrano-Monserrate et al., 2020). Similarly, due to strict lockdown, levels of NO_2 and $PM_{2.5}$ in Wuhan, China dropped by 22.8 $\mu g/m^3$ and 1.4 $\mu g/m^3$, respectively (Zambrano-Monserrate et al., 2020).

However, such containments also have negative consequences to the environment due to the increasing amount of domestic and medical waste that can be harmful and potentially transmit diseases to others unless appropriately treated. In Wuhan, for example, hospitals generated 240 metric tons of medical waste per day compared to 50 tons per day in the pre-COVID-19 period (Zambrano-Monserrate et al., 2020). Similarly, household waste has increased due to reliance on

Table 2
Summary of articles in research clusters.

Author(s)	Purpose	Sample	Key findings
Cluster 1: COVID-19 and the environmental degradation			
Wang and Su (2020)	To explore the impact of COVID-19 on the environment	China	• Significant reduction of air pollution due to full or partial lockdown in the short run, which results in reduced GHG • Findings do not support the reduction of GHG in the long run because, after the removal of lockdown, the economic activities and traffic will be higher, which may result in more energy consumption and higher GHG emissions
Zambrano-Monserrate et al. (2020)	To study the indirect effect of COVID-19 on the environment	China, USA, Italy, and Spain	• COVID-19 improved air quality, beaches and reduced noise levels • It increased the bulk amount of domestic and medical waste and reduced initiatives to recycle waste • GHGs reduction is for a shorter time period.
Chakraborty and Maity (2020)	To examine the consequences of COVID-19 on environment and society	Global	• COVID-19 helps to recover the environment and create a positive effect on the environment
Saadat et al. (2020)	To explore the environmental aspect of COVID-19	Global	• Improve air and water quality worldwide • Generate bulk amount of medical waste
Cluster 2: COVID-19 and air pollution			
Abdullah et al. (2020)	To examine the impact of MCO of Malaysia on air quality	Malaysia	• Find a significant influence of MCO of Malaysia on reduction of $PM_{2.5}$
Dantas et al. (2020)	To consider the consequences of partial lockdown of COVID-19 on air quality	Rio de Janeiro, Brazil	• CO decreases significantly during lockdown period • NO_2 decreases due to lockdown • PM_{10} reduced to a low level • O_3 increased due to reduction in NO_2
Muhammad et al. (2020)	To explore the level of air pollution before and after the COVID-19 pandemic	China, Spain, France, Italy and USA.	• Air pollution reduced by around 30% during COVID-19. • Mobility reduced by around 90%
Tobías et al. (2020)	To inspect the air pollution level of Barcelona during COVID-19 lockdown	Barcelona, Spain	• NO_2 and BC reduced by 50% during lockdown • PM_{10} reduced • O_3 increased by more than 50% during lockdown
Cluster 3: COVID-19 and climate/meteorological factors			
Bashir et al. (2020)	To consider the correlation between climate indicators and COVID-19	New-York city, USA.	• Average and minimum temperature, and quality of air significantly influence the COVID-19 transmissions.
Tosepu et al. (2020)	To examine the outcome of weather on COVID-19 transmissions	Jakarta, Indonesia	• Average temperature significantly influences COVID-19 transmissions
Şahin (2020)	To explore the consequences of weather on COVID-19 pandemic	Turkey	• Wind shows a positive correlation with COVID-19 cases • Crowds in the city are positively associated with COVID-19 infection
Zhu et al. (2020)	To study the outcome of meteorological factors and air pollution on COVID-19 infections	China	• Positive relationship between $PM_{2.5}$, PM_{10}, CO, NO_2 and $O_{3,}$ and COVID-19 transmissions • Adverse relationship between SO_2 and COVID-19 transmissions.
Pirouz et al. (2020)	To study the influence of climate and urban factors on COVID-19 cases	Italy	• Climate factors affect the trend of confirmed cases of COVID-19
Qi et al. (2020)	To examine the influence of metrological factors, such as temperature and humidity on COVID-19 cases	30 Chinese provinces	• Significant negative influence of temperature and humidity on daily cases of COVID-19 • Interaction effect of temperature and humidity is robust in case of daily COVID-19 cases
Gupta et al. (2020)	• To examine the outcome of weather on COVID-19 transmission • To predict the transmission risk of India by following the weather factors of the US	US	• Temperature and humidity can predict COVID-19 transmission for the US
Ma et al. (2020)	To inspect the consequences of meteorological parameters on COVID-19 deaths	Wuhan, China	• Significant positive correlation with diurnal temperature with COVID-19 deaths • Negative relationship between humidity and COVID-19 deaths
Sobral et al. (2020)	• To explore the impact of meteorological factors on COVID-19 transmissions • To examine the outcome of meteorological factors on COVID-19 deaths	International sample	• Negative relationship between temperature and COVID-19 transmission • Positive relationship between precipitation and COVID-19 transmission • Countries that have higher rainfall experience an increase in COVID-19 transmission • There is no relationship between temperature or precipitation on COVID-19 mortality
Ogen (2020)	To study the outcome of NO_2 on COVID-19 mortality	Italy, Spain, France and Germany.	• Long-term exposure of NO_2 increases fatalities due to COVID-19
Cluster 4: COVID-19 and temperature			
Briz-Redón and Serrano-Aroca (2020)	To study the consequences of temperature on COVID-19 transmissions	Spain	• Insignificant impact of temperature on COVID-19 transmissions
Prata et al. (2020)	To examine the outcome of temperature on COVID-19 transmissions in Brazil	Brazil	• At average temperature below 25.8 °C, each 1 °C increase was associated with a −4.895% drop in daily confirmed COVID-19 cases
Xie and Zhu (2020)	To explore the effect of temperature on COVID-19 transmission	China	• Negative relationship between temperature and COVID-19 transmission when the temperature is between 16.8 °C and 27.4 °C
Shi et al. (2020)	To examine the outcome of temperature on COVID-19 transmissions	China	• Temperature shows a positive linear association with COVID-19 cases when the temperature is lower than 3 °C • No evidence found on COVID-19 transmission cases due to increase in temperature • "Temperatures above about 8 to 10 °C appear to decrease the incidence of COVID-19" (Shi et al., 2020 p. 3)
Jahangiri et al. (2020)	To consider the consequences of 'ambient temperature' and 'population size' on COVID-19 transmissions	Iran	• Temperature reduces COVID-19 transmission cases

online shopping and home delivery (Zambrano-Monserrate et al., 2020). Thus, the post-lockdown period is crucial to maintain a low level of environmental pollution and take necessary steps to dispose harmful medical waste to stop future transmission of COVID-19 and other infectious pathogens. Fig. 1 summarises the positive and negative impacts of COVID-19 on environmental degradation.

3.1.1. Future research

Future studies may consider other indicators, such as weather, industrial operations, traffic and burning of biomass that affect the particulate matter ($PM_{2.5}$). Apart from the reduction of $PM_{2.5}$, the lockdown is not ostensibly related to $PM_{2.5}$ (Abdullah et al., 2020). Likewise, factors associated with a decline in air pollution during COVID-19 lockdown need further attention. Future research may replicate studies on the impacts of COVID-19 on the environment in the context of different countries, such as the consequence of lockdown on environmental quality (Wang and Su, 2020).

3.2. COVID-19 and air pollution

Every year, air pollution triggers serious health issues, and a large number of people die due to the consequences of air pollution. In 2017 alone, air pollution caused 4.9 million deaths globally, with low-income economies suffering the most (Global Burden of Disease Collaborative Network, 2018). In the context of COVID-19, studies found a significant reduction of air pollution during the lockdown (Dantas et al., 2020; Tobías et al., 2020). Air pollutants, such as NO_2 and carbon dioxide (CO_2) emissions dropped significantly due to the halt in industrial and vehicle operations worldwide (Paital, 2020). Due to the drop in fossil fuel consumption, air pollution has dropped drastically in several countries, such as China, Italy, the USA, and India (Paital, 2020). NO_2 levels in major Indian cities such as Ahmedabad, Mumbai, and Pune decreased between 40 and 50% at the time of lockdown (Wright, 2020). In Europe, CO_2 levels are expected to drop by 390 million tonnes due to lockdown (Paital, 2020). In the USA, carbon emissions also dropped around 40% during lockdown due to lower traffic (Paital, 2020).

Moreover, Dantas et al. (2020) reported that carbon monoxide (CO), NO_2, and 'particulate matter with a diameter small or equal to 10 μm' (PM_{10}) decreased significantly during the global shutdown, while ozone (O_3) increased due to reduction in NO_2. In line with Dantas et al. (2020) and Tobías et al. (2020) found that NO_2 and black carbon (BC) reduced by 50% during the lockdown period, while PM_{10} was reduced to some extent. Conversely, the level of O_3 was increased by more than 50% during lockdown in Barcelona. Likewise, in Barcelona, NO_2, and BC declined between 45 and 51% (Tobías et al., 2020).

Furthermore, Abdullah et al. (2020) and Muhammad et al. (2020) studied the impact of COVID-19 on pollution before and after the restriction period. In the context of Malaysia, Abdullah et al. (2020) found that the MCO (movement control order) had a significant influence on the reduction of $PM_{2.5}$. Muhammad et al. (2020) found that the lockdown resulted in a 30% drop in air pollution while mobility was restrained by approximately 90%. Fig. 2 summarises the indirect impacts of COVID-19 on air pollution due to lockdowns.

3.2.1. Future research

Future research should include meteorological factors and further test the effect of lockdown on air quality (Dantas et al., 2020). Moreover, future research may explore the cause behind the low reduction of PM_{10} during lockdown compared to NO_2 and BC, and might consider the overall pollution during lockdown without taking the meteorological factors into account (Tobías et al., 2020).

3.3. COVID-19 and climate/meteorological factors

Similar to other communicable diseases, the transmission of COVID-19 is also greatly influenced by climate system. Significant parameters of climate are temperature, humidity, rainfall, and wind speed. Studies found a significant association among meteorological factors and COVID-19. Bashir et al. (2020) stated that quality of air significantly increased the spread of COVID-19 infections in New York City. In addition, Şahin (2020) and Zhu et al. (2020) examined the influence of weather and meteorological factors on COVID-19 transmissions in the cases of Turkey and China, respectively. Şahin (2020) reported positive associations of wind speed and crowd in cities with high COVID-19 transmission rates. Zhu et al. (2020) found that $PM_{2.5}$, PM_{10}, CO, NO_2 and O_3 all had a positive relation with COVID-19 transmissions, but they also found a negative association between sulphur dioxide (SO_2) and COVID-19 transmissions. "A 10-$\mu g/m^3$ increase (lag0–14) in $PM_{2.5}$, PM_{10}, NO_2, and O_3 was associated with a 2.24% (95% CI: 1.02 to 3.46), 1.76% (95% CI: 0.89 to 2.63), 6.94% (95% CI: 2.38 to 11.51), and 4.76% (95% CI: 1.99 to 7.52) increase in the daily counts of confirmed cases, respectively. However, a 10-$\mu g/m^3$ increase (lag0–14) in SO_2 was

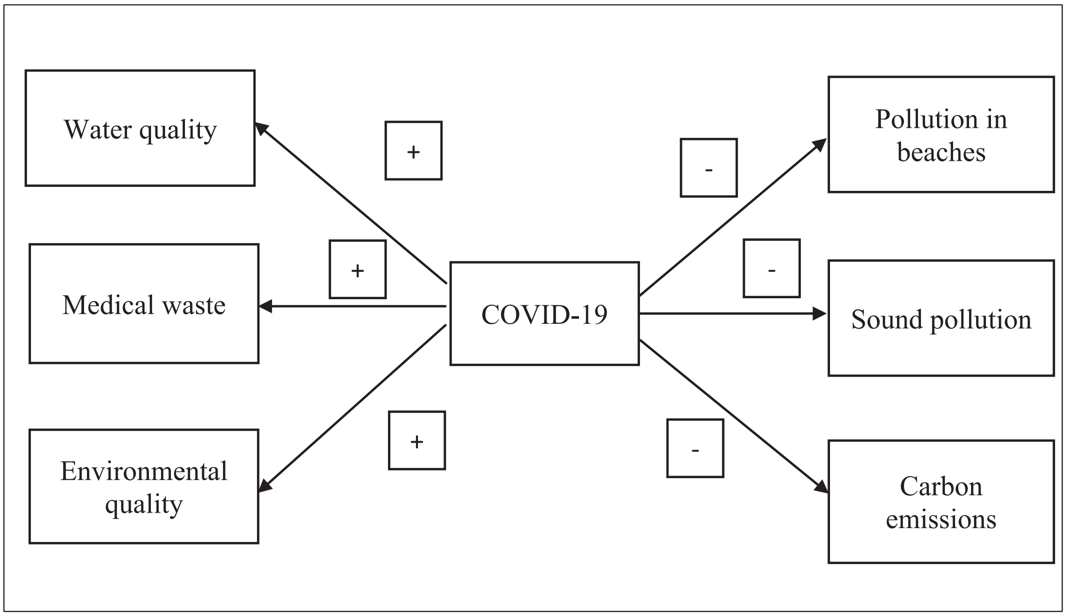

Fig. 1. Impacts of COVID-19 on environmental degradation.

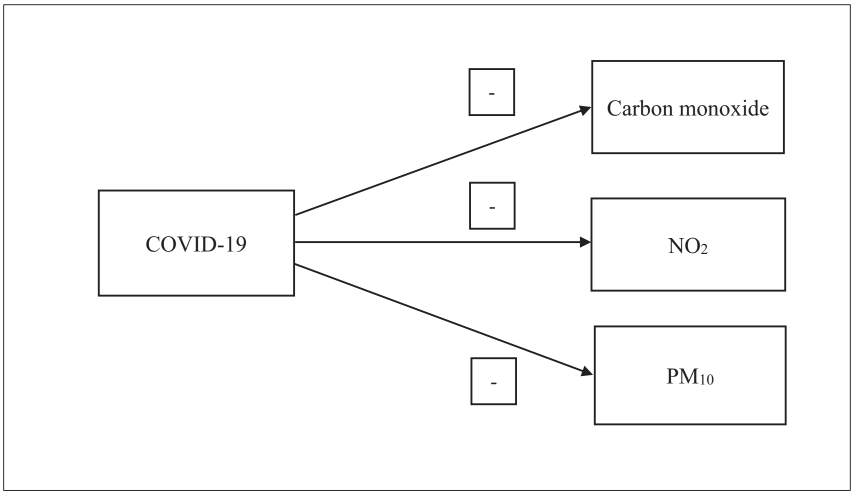

Fig. 2. Indirect impacts of COVID-19 on air pollution.

associated with a 7.79% decrease (95% CI: −14.57 to −1.01) in COVID-19 confirmed cases" (Zhu et al., 2020, p. 1).

Moreover, several studies have sought to understand the effect of climate and urban factors on COVID-19 transmissions (Gupta et al., 2020; Pirouz et al., 2020; Qi et al., 2020). Pirouz et al. (2020) found that climate factors disturb the trend of confirmed cases of COVID-19. Qi et al. (2020) scrutinised the validity of metrological factors such as temperature and humidity on COVID-19 cases in 30 Chinese provinces. They found that temperature and humidity had a significant adverse impact on daily cases of COVID-19, and that the interaction effect of temperature and humidity is robust in case of daily COVID-19 cases. Qi et al. (2020) found that a 1 °C rise in average daily temperature decreased the daily rate of COVID-19 cases by between 36% and 57% when relative humidity was between 67% and 85.5%. Likewise, a 1 °C rise in relative humidity decreased the daily COVID-19 cases by between 11 and 22% when the average daily temperature was between 5.04 °C and 8.2 °C (Qi et al., 2020). Additionally, Gupta et al. (2020) suggested that temperature and humidity can predict COVID-19 transmission in the USA.

While several studies have emphasised the consequences of climate indicators on COVID-19 transmissions, some studies have inspected the phenomenon from the opposite point of view and revealed a mixed (positive and negative) impact of climate factors on COVID-19 mortality (Ma et al., 2020; Ogen, 2020; Sobral et al., 2020). Ma et al. (2020) tested the influence of meteorological factors on COVID-19 death and revealed a significant positive association with diurnal temperature with COVID-19 death, and a negative association between humidity and COVID-19 death. Ogen (2020) studied the outcome of NO_2 on COVID-19 mortality in Italy, Spain, France and Germany by applying spatial analysis, revealing that long-term exposure to NO_2 increases fatalities due to COVID-19. However, Sobral et al. (2020) found no association between temperature or precipitation and COVID-19 mortality. Despite mixed results, national governments should contemplate climate indicators to fight the pandemic and take imperative actions based on the climatic characteristics of their nation. Fig. 3 summarises the impacts of meteorological factors on COVID-19 transmission.

3.3.1. Future research

Future research may consider the case of multi-country climate indicators and their consequence on COVID-19 transmissions. Current studies only observe the association between climate indicators and COVID-19, but they do not consider other factors such as the strictness of regulations and the robustness of health-care systems, which can potentially control

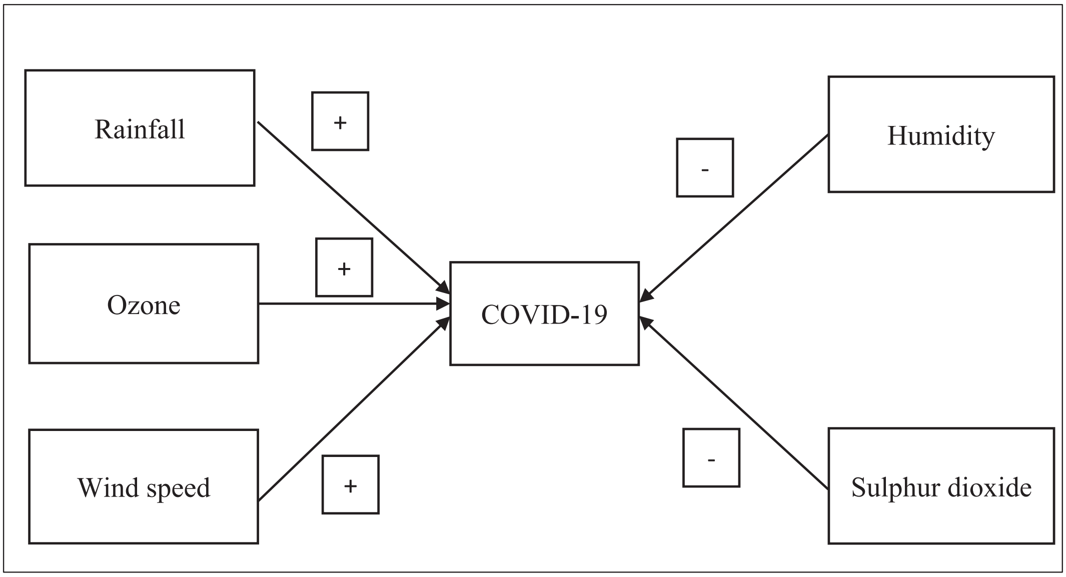

Fig. 3. Impacts of meteorological factors on COVID-19 transmission.

the pandemic. Future studies may also incorporate non-resident citizens who return from abroad and stay in quarantine (Şahin, 2020). Likewise, future studies could consider the age and gender of COVID-19 cases and investigate the interaction effects of these factors and air pollution on COVID-19 transmission, which may reveal novel insights and enable authorities to guide the vulnerable groups accordingly to reduce the transmission and mortality rates (Zhu et al., 2020). Furthermore, in the case of climate factors and COVID-19 transmission, future studies should consider potential risk factors, such as the social and economic status of the residents of provinces, and incorporate the variables in the model to test the effects of metrological factors on COVID-19 (Qi et al., 2020).

3.4. COVID-19 and the temperature

Many countries are struggling to control the increasing transmission of COVID-19. There has been a lot of debate regarding the effect of temperature on COVID-19 transmissions while predicting the spread of the disease in certain warm countries. It has been suggested that the hot and humid climates in India might have been the cause of relatively low transmission rate of COVID-19 cases. However, it has also argued that strict lockdown plays an essential role in the low transmissions of COVID-19 cases (Paital, 2020; Paital et al., 2020). There has been a debate about the negative effect of temperature on COVID-19 transmissions. Researchers have argued for both the negative and positive effects of temperature on COVID-19 transmissions (Chin et al., 2020; Xie and Zhu, 2020). Chin et al. (2020 p. e10) argued that "the virus is highly stable at 4°C, but sensitive to heat. At 4 °C, there was only around a 0·7 log-unit reduction of infectious titre on day 14. With the incubation temperature increased to 70 °C, the time for virus inactivation was reduced to 5 min."

Xie and Zhu (2020) reported that temperature has a positive linear association with COVID-19 cases when the temperature is lower than 3 °C. On the contrary, Shi et al. (2020) showed opposite effects in the context of China and stated that temperatures over 8 °C to 10 °C reduce the daily outbreak of COVID-19 cases (Shi et al., 2020). By using a 'modified susceptible-exposed-infectious-recovered' (M-SEIR) model, they also predict that the outbreak would peak at the beginning of March 2020 in Wuhan, and decline by the end of April. The authors argue that M-SEIR model provides better guidance for prevention of COVID-19 outbreak. Likewise, Prata et al. (2020) found that a 1 °C increase in temperature is linked with a 4.9% decline in daily COVID-19 transmissions when the temperature was lower than 25.8 °C. However, the same study found no evidence for the reduction in COVID-19 transmissions if the temperature is more than 25.8 °C.

Meanwhile, Briz-Redón and Serrano-Aroca (2020) reported an insignificant effect of temperature on COVID-19 transmissions in the context of Spain by employing 'spatio-temporal modelling' techniques. They also incorporated other non-meteorological variables in their analysis, such as age, number of travellers, population density and number of firms. Jahangiri et al. (2020) conducted a sensitivity analysis of 'ambient temperature' and 'population size' on COVID-19 transmissions, finding that 'ambient temperature' displays low sensitivity to COVID-19 transmissions, whereas 'population size' indicates high sensitivity to COVID-19 transmissions. Fig. 4 summarises the impacts of temperature on COVID-19.

3.4.1. Future research

Future research should consider the non-meteorological and spatial influences on COVID-19 transmissions (Briz-Redón and Serrano-Aroca, 2020). The majority of extant studies have been based on countries with low temperatures, so future research should consider countries with high temperature and humidity.

4. Critical reflection on methodologies

Table 3 presents the data and methodologies used in the sample of revised studies. In terms of methodology, the majority of the articles used quantitative analysis to examine the impacts of COVID-19 on the environment, and vice-versa. Out of 57 articles, four employed descriptive statistics and trend analysis (Chakraborty and Maity, 2020; Gupta et al., 2020; Pirouz et al., 2020; Wang and Su, 2020), and four applied graphical analysis, data plotting and comparison between graphs to reach inference (Muhammad et al., 2020; Shi et al., 2020; Tobías, 2020; Zambrano-Monserrate et al., 2020). Fig. 5 provides a summary of the applied methods.

Descriptive and graphical analyses have limitations to postulate robust findings. Such analysis provides a summary of the sample studied but the findings are limited to theoretical or empirical explanations of the research problem. Some existing studies applied spatial analysis to solve complex location-oriented issues (Briz-Redón and Serrano-Aroca, 2020; Ogen, 2020). Dynamic spatio-temporal models provide robust results compared to descriptive and graphical analyses (Hefley et al., 2017; Kang et al., 2020).

In addition, a large number of studies applied Kendall and Spearman's rank correlation analysis to test the correlation between COVID-19 and the environment (Bashir et al., 2020; Şahin, 2020; Tosepu et al., 2020; Zhu et al., 2020). The Spearman rank correlation has some limitations; for example, data should be linear and independent from each other. If the data is non-linear, it may produce misleading inferences. Moreover, some studies considered various regression analysis to examine the influence of metrological factors on COVID-19 and vice-versa. Examples include multivariate linear regression (Pirouz et al., 2020), panel regression (Sobral et al., 2020), piecewise linear regression (Xie and Zhu, 2020), polynomial regression (Prata et al., 2020), and locally weighted regression (Shi et al., 2020).

The fact that the majority of the studies applied linear regression meant that non-linearity and endogeneity issues have been overlooked. To address the issue of non-linearity, existing studies also considered

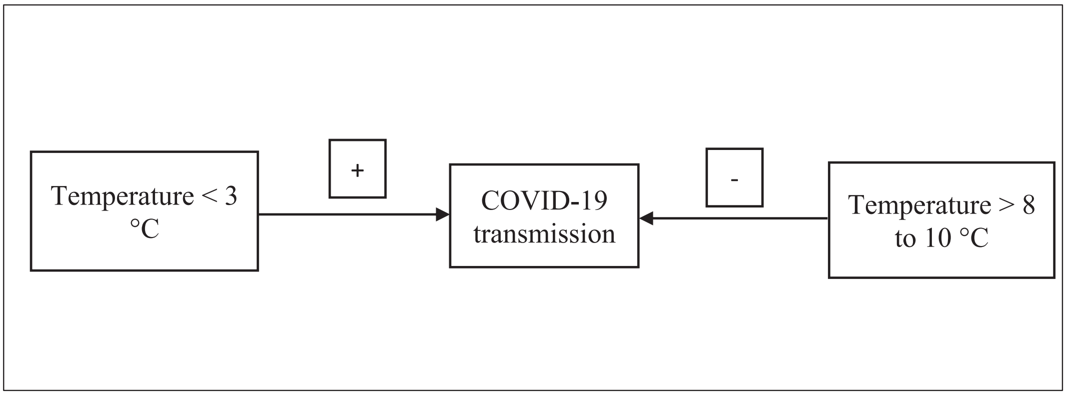

Fig. 4. Impacts of temperature on COVID-19.

Table 3
Data and methodology used in the articles in research clusters.

Author(s)	Data	Methodology
Cluster 1: COVID-19 and the environmental degradation		
Wang and Su (2020)	• GHG • NO_2 • COVID-19	• Descriptive and trend analysis
Zambrano-Monserrate et al. (2020)	• $PM_{2.5}$ • NO_2 concentrations • Clean beaches • Noise level • Domestic and medical waste	• Graphical analysis
Chakraborty and Maity (2020)	• Not specified	• Descriptive study
Cluster 2: COVID-19 and air pollution		
Abdullah et al. (2020)	• Air Pollutant Index of Malaysia. • COVID-19 daily cases.	• Comparative study based on air pollution index of before and during the MCO
Dantas et al. (2020)	• CO • NO_2 • O_3 concentrations	• Standard methods by using R statistical software
Muhammad et al. (2020)	• NO_2 • Air pollution data from National Aeronautics and Space Administration (NASA) and European Space Agency (ESA)	• Graphical comparison
Tobías et al. (2020)	• PM_{10} • NO_2 • SO_2 • O_3 • BC	• Data plotting by using 'Google Earth Engine'
Cluster 3: COVID-19 and climate/meteorological factors		
Bashir et al. (2020)	• Average, minimum and maximum temperature • Rainfall • Average humidity • Wind speed • Air quality	• Kendall and Spearman rank correlation tests
Tosepu et al. (2020)	• Temperature • Humidity • Rainfall • COVID-19 daily cases.	• Spearman-rank correlation tests
Şahin (2020)	Weather factors: • Temperature • Due point • Humidity • Wind speed	• Spearman's correlation coefficients
Zhu et al. (2020)	• $PM_{2.5}$ • PM_{10} • SO_2 • CO • NO_2 • O_3	• Spearman correlation coefficients • Generalized additive model
Pirouz et al. (2020)	Climate factors: • Temperature • Humidity • Wind speed Urban factors: • Density of population	• Trend analysis • Multivariate linear regression
Qi et al. (2020)	• Temperature • Humidity • COVID-19	• Generalized additive model
Gupta et al. (2020)	• Temperature • Humidity • COVID-19 daily cases	• Descriptive analysis
Ma et al. (2020)	• Temperature • Diurnal temperature • Absolute and relative humidity • COVID-19 daily cases	• Generalized additive model
Sobral et al. (2020)	Meteorological variables • Temperature • Precipitation Control variables • Density of population • Exposure time Dummy variable • Month	• Panel data regression model
Ogen (2020)	• NO_2 • COVID-19 fatality	• Spatial analysis
Cluster 4: COVID-19 and temperature		
Briz-Redón and Serrano-Aroca (2020)	Meteorological variable: • Temperature Non-meteorological variables: • Population density • Age • Number of travellers • Number of firms	• Spatio-temporal modelling techniques
Prata et al. (2020)	• Temperature • COVID-19 daily cases	• Generalized additive model in both linear and non-linear effect • Polynomial (cubic) regression model is applied
Xie and Zhu (2020)	• Temperature • COVID-19 daily cases	• Generalized additive model • Piecewise linear regression
Shi et al. (2020)	• Temperature • COVID-19 daily cases	• 'Locally weighted regression' • 'Smoothing scatterplot' • 'Distributed lag nonlinear models' • 'Random-effects meta-analysis'
Jahangiri et al. (2020)	• Ambient temperature • Population size • COVID-19 transmission cases	• Receiver operating characteristics (ROC) • Sensitivity and specificity analyses

generalized additive model (Ma et al., 2020; Prata et al., 2020; Qi et al., 2020; Xie and Zhu, 2020; Zhu et al., 2020). Moreover, studies focused on specific methods to address other factors; for example, Jahangiri et al. (2020) applied receiver operating characteristics to test the sensitivity and specificity of temperature and population size on COVID-19 transmission. Moreover, Dantas et al. (2020) used standard methods to investigate the consequences of partial lockdown on air quality in Brazil. Based on the above reflection, it is evident that existing studies have focused on a diverse set of methods to examine COVID-19 and the environment and vice-versa. Metrological factors may have possible nonlinearity, endogeneity and simultaneity issues. Thus, to avoid misleading findings, future studies should be careful when dealing with metrological data. Misinterpretation of findings may cause severe damage to peoples' health, safety and the environment.

5. Conclusion

This study has presented a critical review of the existing studies on the environmental causes and consequences of COVID-19. We have explored the issue by looking at both sides of the coin; that is, the impact of

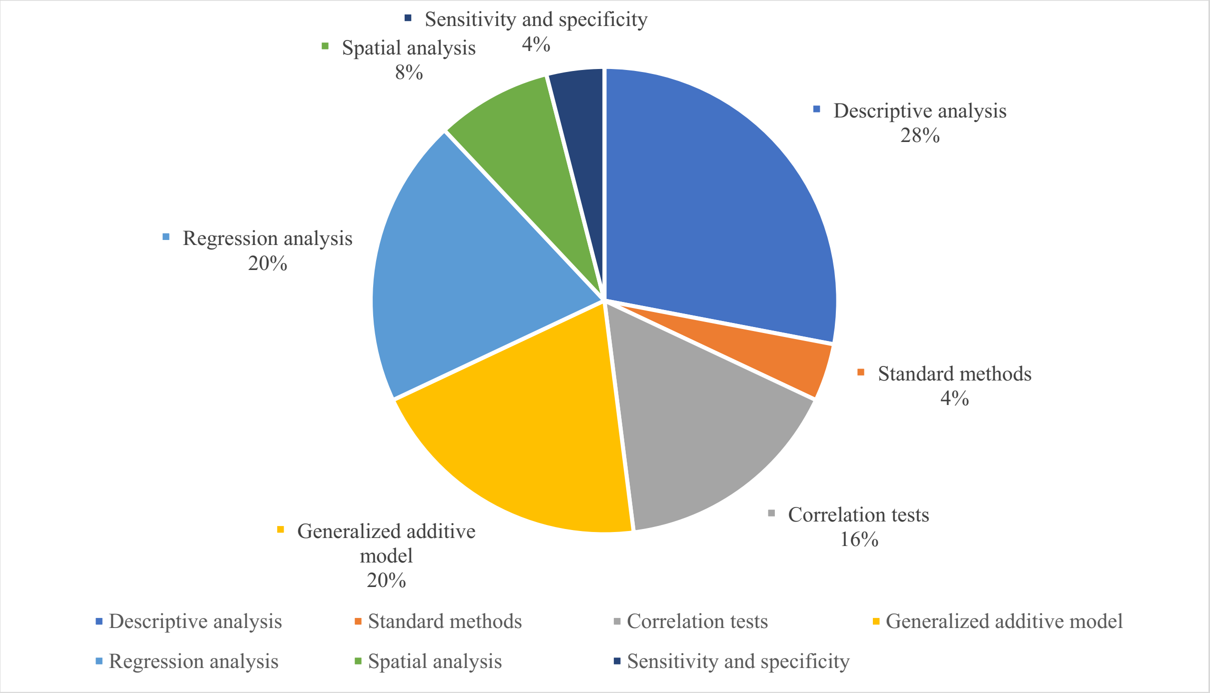

Fig. 5. Distribution of methodologies applied in COVID-19 and environment research.

COVID-19 on the environment and the impact of environmental indicators on COVID-19 transmissions and mortality. Based on a critical review of 57 studies on the topic, we conclude that the COVID-19 pandemic has led to improved environmental quality. Due to COVID-19, actions taken by governments across the world have led to significant reductions in environmental pollution and improvements in environmental quality, particularly, in countries with severe COVID-19 transmission such as China, USA, Italy and Spain. These countries experienced sharp reductions in carbon emissions, air pollution, sound pollution and pollution in beaches. However, these reductions were due to lockdown and were persistent within the lockdown period. Whether the environmental quality will persist in the long-run is unknown. Besides, we have observed that environmental factors also contributed to both the spread and reduction of COVID-19 transmission and mortality rates. A significant number of reviewed articles provide positive, negative, mixed and inconclusive results of the influence of metrological factors, such as temperature, wind speed and humidity, on COVID-19 transmission and mortality. Future research should attempt a meta-analysis to provide more conclusive evidence.

Moreover, we contribute to the existing literature on COVID-19 and the environment by critically analysing existing research and identify the gaps for future research. We tabulated different methodologies and data sources (see Table 3) applied by researchers and discussed significant methodological outcomes. Future studies may use the data sources and methodologies used as a reference point and conduct cross-country analysis to understand similarities and differences in the findings on distinct methodological and country settings. In Table 4, we propose cluster-wise future research questions to explore the dynamics between COVID-19 and the environment.

Finally, this study has certain limitations. It was limited to a certain period – November 2019 to May 2020 – and only included studies published since the origin of COVID-19. We find that there is a lack of research on COVID-19 and environmental degradation. The majority of research emphasises the impact of climate indicators on COVID-19 transmission and mortality. Only a limited number of studies have examined the influence of COVID-19 on environmental quality and degradation. It is evident from the published research that carbon emissions

Table 4
Future research questions.

Author(s)	Future research
Cluster 1: COVID-19 and the environmental degradation	
Wang and Su (2020)	1. Does COVID-19 have any effect on the environment in the case of highly populated countries? 2. Does the environmental quality persist post-lockdown?
Cluster 2: COVID-19 and air pollution	
Abdullah et al. (2020)	3. Do weather, traffic, industrial operations and burning of biomass reduce the $PM_{2.5}$ apart from MCO?
Tobías et al. (2020)	4. Is there any significant reason behind the low reduction of PM_{10} during lockdown compared to NO_2 and BC? 5. Does overall pollution during lockdown differs if the meteorological factors are not considered?
Cluster 3: COVID-19 and climate/meteorological factors	
Bashir et al. (2020)	6. Does the impact of COVID-19 on climate change differ between more-affected and less-affected countries?
Zhu et al. (2020)	7. Does air pollution have any effect on the age and gender of COVID-19 transmissions?
Qi et al. (2020)	8. Does the social and economic status of the resident of provinces influence the effect of metrological factors on COVID-19?
Gupta et al. (2020)	9. Is there any influence of demographic variations, infrastructure of healthcare and social policies and their combined effect on COVID-19 transmission?
Ma et al. (2020)	10. Does the intervention of governments and medical resources have any effect on COVID-19 fatality?
Sobral et al. (2020)	11. Does solar radiation effect COVID-19 transmission and mortality?
Ogen (2020)	12. Do age, disease, pre-exposure to nitrogen dioxide and hypercytokinemia have any effect on COVID-19 mortality?
Cluster 4: COVID-19 and temperature	
Briz-Redón and Serrano-Aroca (2020)	13. Can the interaction between climate and human conduct be a confounder in the connection among climate circumstances and COVID-19 transmissions? 14. Do non-meteorological and spatial factors influence COVID-19 transmissions?

and air pollution reduce significantly due to lockdown. However, it is crucial to investigate whether the reduction of pollution will continue in the post-lockdown. Likewise, research on how to deal with a large volume of medical waste, and how to recycle and decompose waste in the post-lockdown period is not evident in the literature. Future research should provide necessary policy recommendations and propose a holistic model for government and regulatory bodies on how to control environmental pollution and recycle medical waste during post-lockdown.

CRediT authorship contribution statement

Mohammad Hassan Shakil: Conceptualization, Data curation, Formal analysis, Writing - original draft. **Ziaul Haque Munim:** Methodology, Supervision, Writing - review & editing. **Mashiyat Tasnia:** Validation, Writing - review & editing. **Shahin Sarowar:** Validation, Writing - review & editing.

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.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.scitotenv.2020.141022.

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