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COVID-19 and environmental concerns: A rapid review

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ABSTRACT

COVID-19 has slowed global economic growth and consequently impacted the environment as well. Parallely, the environment also influences the transmission of this novel coronavirus through various factors. Every nation deals with varied population density and size; air quality and pollutants; the nature of land and water, which significantly impact the transmission of coronavirus. The WHO (Ziaepour et al., 2008) [1] has recommended rapid reviews to provide timely evidence to the policymakers to respond to the emergency. The present study follows a rapid review along with a brief bibliometric analysis of 328 research papers, which synthesizes the evidence regarding the environmental concerns of COVID-19. The novel contribution of this rapid review is threefold. One, we take stock of the diverse findings as regards the transmission of the novel coronavirus in different types of environments for providing conclusive directions to the ongoing debate regarding the transmission of the virus. Two, our findings provide topical insights as well as methodological guidance for future researchers in the field. Three, we inform the policymakers on the efficacy of environmental measures for controlling the spread of COVID-19.

1. Introduction

The novel coronavirus disease (also known as COVID-19), which emerged from Wuhan, China, in December 2019, has spread all over the world with over 112 million confirmed cases (as of 23rd February 2021) [2]. On the grounds of rising COVID-19 cases worldwide, the World Health Organization declared COVID-19 as a global health emergency on 30 January 2020 [3]. COVID-19 (SARS-CoV-2) is the third highly pathogenic human coronavirus that developed after the Severe Acute Respiratory Syndrome (SARS) and the Middle East Respiratory Syndrome (MERS). The rapid transmission of the virus is the biggest challenge of COVID-19. Governments worldwide are resorting to measures such as shutdowns, lockdowns, travel restrictions, maintaining social distancing, curbing social gatherings, etc., to control the spread of the virus. Reduction in the economic activities leading to slower global economic growth is the apparent result of these measures. The reduced economic activities lead to lower carbon emissions, improved air quality, low pollution levels, and enhanced ozone layer on the earth [4]. A growing body of evidence suggests that the atmosphere has an effect on the transmission of the novel coronavirus through inanimate surfaces,

owing to meteorological factors such as temperature, humidity, wind speed, and rainfall [5–7]. Emerging literature observes that the speed of transmission of the SARS-CoV-2 is different across the countries due to the variability in air quality and pollutants, the nature of land and water. In this way, a growing literature in the field studies the bi-directional relationship between COVID-19 transmission and environmental conditions.

Since the emergence and acceleration of COVID-19 have led to global pandemic situations, WHO [1] has recommended rapid reviews to provide timely evidence to the policymakers to respond to the emergency. Some rapid reviews have attempted to study the COVID-19 related research [8–11]. However, despite the availability of more than 120 empirical papers investigating the relationship between COVID-19 and the environment, no review on the environmental concerns of COVID-19 is available. Such a review is severely required since the findings of the COVID-19-environmental relationship are inconclusive and need to be synthesized. Such synthesis would not merely contribute theoretically towards the body of knowledge studying the pandemic transmission, but would also be immensely useful for the policymakers in controlling the spread of ongoing and future pandemics.

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This rapid review intends to make this contribution by dealing with the environmental concerns of COVID-19. For this rapid review, we include the papers investigating the role of environmental factors on COVID-19 and those examining the environmental impact of COVID-19. Furthermore, the study also involves a brief bibliometric analysis of relevant literature in the concerned field of research, providing a comprehensive overview of the literature leading to significant propositions. The bibliometric information of documents is retrieved from Web of Science database and analyzed using Bibliometrix R package [12].

The novel contribution of this rapid review is threefold. One, we take stock of the diverse findings regarding the transmission of the novel coronavirus in different types of environments for providing conclusive directions to the ongoing debate regarding the transmission of the virus. Two, our findings offer topical insights as well as methodological guidance for future researchers in the field. Three, we inform the policymakers on the efficacy of environmental measures for controlling the spread of COVID-19.

The paper proceeds as follows: the next section outlines the methodology applied for this review; the third section discusses the themes; the fourth section offers future directions to the researchers, and the last section concludes.

2. Research methodology

We conduct a rapid review to synthesize the evidence regarding the impact of the environment on COVID-19 and vice-versa. Rapid reviews follow all the steps of a systematic review with just a simplified and accelerated process to present knowledge on time [9].

A search of the literature was made from the Web of Science database, having multidisciplinary and impactful research [13]. The search strategy involved the combination of keywords related to the novel coronavirus ("COVID-19" OR "SARS-CoV-2" OR "novel coronavirus") and environment ("environment" OR "temperature" OR "weather" OR "climate" OR "humid" OR "air" OR "water" OR "land"). We also searched the preprint platform - MedRxiv. The studies included in this rapid analysis are those that are relevant to both COVID-19 and the environment, are written in English, and were published after the first case of novel coronavirus was identified in late 2019 [14]. Studies in which the entire text or relevant data could not be found, are also excluded. The screening process is illustrated using a PRISMA flow diagram [14] (see Fig. 1).

The initial search yielded 418 studies from the Web of Science database and MedRxiv preprint platform, out of which 67 records were published before November 2019, and 23 full texts were excluded since

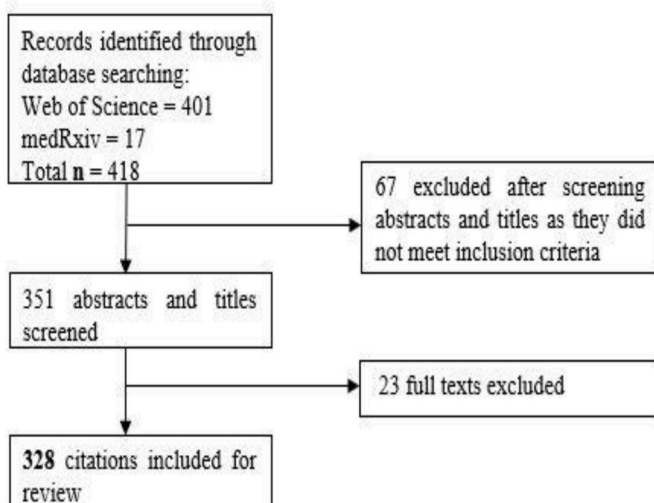


Fig. 1. Identification and screening of research papers reviewed.

those did not relate to environmental science and hence, did not fall under inclusion criteria. We performed a bibliometric analysis (as discussed in section 3) on the final list of 328 citations. After the full-text analysis, the in-depth investigation leads us to the six themes (see Fig. 2), as discussed in section 4.

3. A brief bibliometric review

This section presents the results and findings of the bibliometric analysis of the selected research articles.

3.1. Source Impact

The top 10 publishing sources (journals) account for almost 50% of the selected articles under study (Fig. 3). Fig. 3 shows h-, g-, and m-index of these ten sources. The h-index is an author-level metric that calculates the productivity and citation impact of the publications of a researcher [15]; g-index is the unique largest number such that top g papers together receive g^2 or more citations [16]; while the m-index is the median number of citations received by papers in the h-core [17].

3.2. Authors' impact

Table 1 depicts the Impact scores for the top 10 authors in the concerned field, highlighting their h-index and g-index along with total citations and publications. Since, m-index is the h-index divided by the time (years) between the first and most recent publication, hence m-index is not available due to such recent publications.

3.3. Country collaboration map

In the country collaboration map (Fig. 4), countries in dark blue shades (USA, Alaska, China and India) have a maximum number of publications, with USA being the most collaborated country with several countries worldwide. The blue shade represents the frequency of publications from a country in this field whereas the thickness of the pink lines depicts collaboration between 2 countries. There are limited articles from African countries.

3.4. Prominent Keywords

Fig. 5 shows that the most frequent keywords in the reviewed literature are pollution, impact, pm2.5, transmission, ozone, quality, health, mortality, temperature, coronavirus, outbreak, emissions, China, survival, exposure and so on as we go along the assessment of the articles pertaining to Covid-19 and environment. Pollution has arisen as a key concern across the globe during Covid-19, be it linking pollution with a rise in fatality rate [18–21] or discussing the impact of Covid-19 pandemic on environmental pollution is most often discussed concern in the research articles [22–24]. Further, the role of PM 2.5 concentration, emissions and temperature on ozone layer and framing that outbreak of coronavirus and rise in mortality can be driven by impact of environmental factors is also a widely studied topic among the articles assessed for this study [25–31].

3.5. Multi-Dimensional Scaling

Fig. 6 represents the embedding of core keywords within the extant literature on the relationship between covid-19 and environmental factors. SARS, outbreak, influenza are the inliers for core themes coming from previous studies. The other clustered keywords clustered (humidity, temperature, air-pollution, PM 2.5, pollution, nitrogen-dioxide, aerosols, particles, SARS-cov-2, China) are preferred and closely depict the dimensions of the research. For instance, studies in past have concentrated on themes as SARS-cov-2 [32–36], transmission [31,37,38], humidity [39–41], air-pollution [28,42,43]. The outliers located at

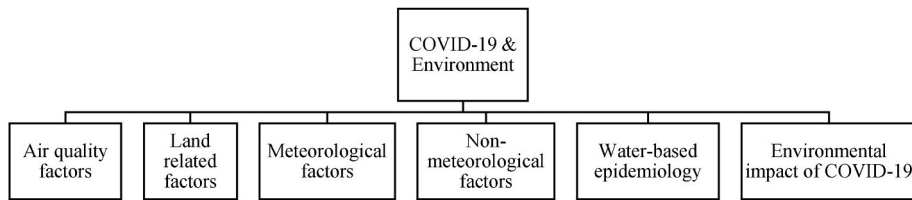


Fig. 2. Thematic framework.

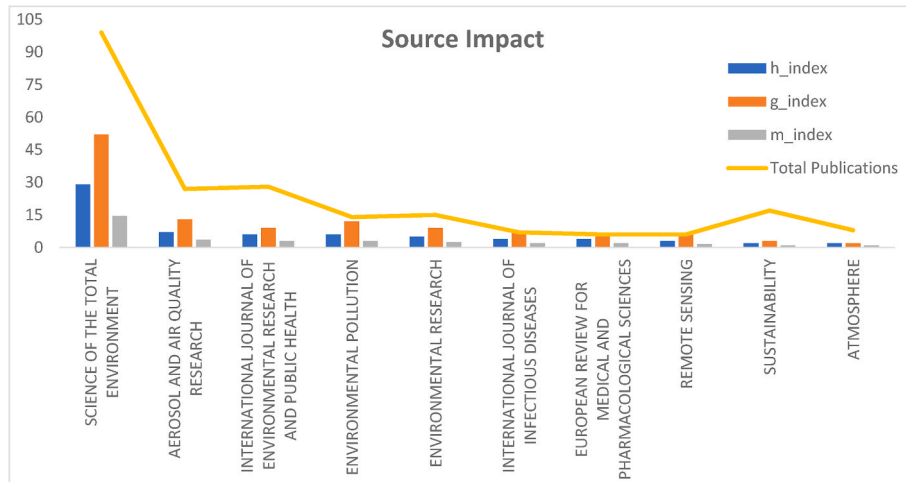


Fig. 3. Source impact.

Table 1 Authors' impact.

Author	h_index	g_index	Total Citations	Total Publications
GAUTAM S	4	5	106	5
SHAHZAD U	4	4	72	4
KUMAR S	3	6	40	6
ZHANG JJ	3	5	74	5
CUI KP	3	4	72	4
FAREED Z	3	4	65	4
LI Y	3	4	20	4
SHAHZAD F	3	4	65	4
WAN S	3	4	72	4
WANG YF	3	4	72	4

the extremes are weather, cities, impact, performance show these words are less embedded in the core themes of the literature and are more distantly embedded in previous research.

The blue keywords cluster of diseases, emissions, NO₂, aerosol, climate change, pollutants, present embodiment of themes within the realm of outliers as covid-19, index, PM₁₀, region. Therefore, future research may study the role of outliers and inliers, thereby catering to the core theme -impact of the environment on Covid-19 in a much broader sense.

4. Thematic discussion

Many factors, including climatic factors, geographical factors, water-

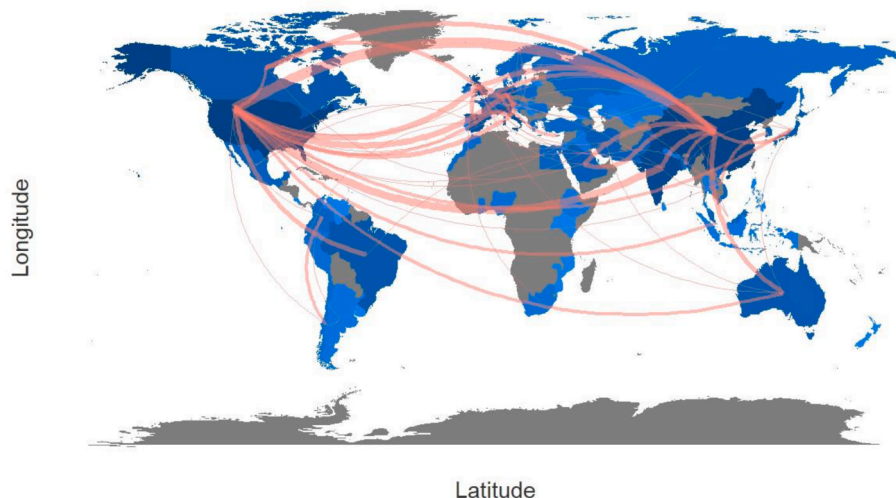


Fig. 4. Country collaboration map.

Table 2
Prominent studies on environmental concerns of COVID-19.

Studies	Country	Methods	Model
Studies finding that air quality factors impact covid-19 transmission			
Filippini et al. [43]	Italy	Empirical	Multivariable negative binomial regression model
Naqvi et al. [47]	India	Empirical	Correlation
Wang et al. [48]	China	Empirical	Generalized additive models
Sharma et al. [49]	India	Empirical	
Xie and Zhu [50]	China	Empirical	Generalized additive model (GAM)
Ong et al. [51]	Singapore	Experimental and Observational	Real-time reverse transcriptase-polymerase chain reaction (RT-PCR)
Bashir et al. [52]	California	Empirical	Spearman and Kendall correlation tests
Al-Rousan and Al-Najjar [53]	China	Empirical	ARIMA model
Zoran et al. [54, 55]	Italy	Empirical	
Zhu et al. [56]	China	Empirical	Generalized additive model (GAM)
Poole [57]	Global	Observational	Deterministic atmospheric weather modeling
Prata et al. [58]	Brazil	Empirical	Generalized Additive Model (GAM)
Gupta et al. [59]	USA	Empirical	Distribution model
Ficetola and Rubolini [60]	Global	Empirical	Linear Mixed Model
Kumar [61]	India	Empirical	HYSPLIT (NOAA) forward trajectories model
Chin et al. [62]	USA	Experimental	
Jahangiri et al. [64]	Iran	Qualitative - Case study	Receiver operating characteristics (ROC)
Quilodrán et al. [65]	China	Empirical	Generalized additive model (GAM)
Şahin [66]	Turkey	Empirical	
Tosepu et al. [67]	Indonesia	Empirical	
Ahmadi et al. [68]	Iran	Empirical	Sobol's-Jansen methods & Partial Correlation Coefficient (PCC)
Bannister-Meyer et al. [69]	Global	Empirical	A statistical model based on Generalized Linear Regression framework
Shi et al. [71]	China	Empirical	SEIR model
Wang et al. [72]	Global	Empirical	Generalized linear mixture model
Jingyuan Wang et al. [73]	China	Empirical	Fixed/Random effect model
Islam et al. [74]	Global	Empirical	Empirical test - Multilevel mixed-effects negative binomial regression models
Iqbal et al. [75]	China	Empirical	Wavelet Coherence techniques
Pequeno et al. [76]	Brazil	Empirical	Generalized Linear Mixed Model (GLMM)
Rosario et al. [77]	Brazil	Empirical	
Mandal and Panwar [78]	Global	Empirical	Univariate analysis and statistical modeling
Livadiotis [79]	USA and Italian regions	Empirical	
Ujiié et al. [80]	Japan	Empirical	

Table 2 (continued)

Studies	Country	Methods	Model
			Poisson regression analysis
Huang et al. [81]	Global	Empirical	
Iqbal et al. [82]	Global	Empirical	Coefficient of determination model
Méndez-Arriaga [83]	Mexico	Empirical	
Pani et al. [84]	Singapore	Empirical	
Sharma et al. [85]	Top 10 most infected countries	Empirical	Advanced econometric techniques of panel data regression
Shahzad et al. [86]	China	Empirical	Quantile regression model
Sobral et al. [87]	Global	Empirical	Panel Data Model
Y. Wu et al. [88]	Global	Empirical	Log-linear generalized additive model (GAM)
Pirouz et al. [89]	Italy	Empirical	Trend and Multivariate Linear Regression
Jain et al. [90]	Afghanistan, India, Pakistan, Bangladesh, Sri Lanka and Nepal	Empirical	Advanced econometric techniques of panel data regression
Sharma, Tiwari, et al. [91]	Top 15 most infected countries	Empirical	Wavelet Coherence and Partial Wavelet Coherence
Yousefian et al. [5]	Iran	Empirical	
Studies observing that lockdown and social distancing impacts the environment positively			
Ju et al. [92]	Korea	Empirical	Paired <i>t</i> -test, sensitivity analysis
Hashim et al. [93]	Iraq	Empirical	AQI measurement
Chen et al. [94]	China	Empirical	Difference-in-difference approach
Wang et al. [95]	China	Empirical	Community Multi-Scale Air Quality (CMAQ) model
Xu et al. [96,97]	China	Empirical	
Jain and Sharma [98]	India	Empirical	
Nadzir et al. [99]	Malaysia	Empirical	Air Sensor network AIRBOXSense
Gautam [100]	India	Conceptual	
Nakada and Urban [101]	Brazil	Empirical	
Lal et al. [102]	Global	Empirical	Coupled Model Inter-comparison Project (CIMIP-5 model)
Mahato et al. [103]	India	Empirical	
Lokhandwala and Gautam [104]	India	Empirical	
Mahato and Ghosh [105]	India	Empirical	MERRA-2 (Modern Era Retrospective-Analysis for Research and Applications, Version 2)
Chakraborty and Maity [44]	Global	Observational	
Muhammad et al. [106]	China, France, Italy, Spain, USA	Empirical	
Myllyvirta and Dahiya [107]	India	Empirical	
Paital et al. [108]	India	Observational	
Saadat et al. [109]	Global	Conceptual	
Wang and Su [110]	China	Empirical	

(continued on next page)

Table 2 (continued)

Studies	Country	Methods	Model
Zambrano-Monserrate et al. [111]	China, USA, Italy, Spain	Conceptual	
Dantas et al. [112]	Brazil	Empirical	
Thakur et al. [113]	Not Applicable	Conceptual	
McGowan [114]	Global	Conceptual	
Sarkodie and Owusu [115]	Global	Qualitative and empirical	
Atalan [116]	Global	Empirical	Correlation
Maithani et al. [117]	India	Empirical	Getis Ord GI* statistic
Chakraborty et al. [118]	India	Empirical	WQI, TSI, Pearson's correlation coefficient, and "t" test
Studies concluding that long-term exposure to pollutants like NO ₂ and PM _{2.5} can be the primary cause of death from COVID-19			
Ogen [119]	Italy, Spain, France, and Germany	Experimental and Observational	Spatial model
Travaglio et al. [120]	England	Empirical	Negative binomial model
Wu et al. [121]	USA	Empirical	Zero-inflated negative binomial mixed models

inflammatory stimuli on the respiratory tract [122]. Zhu et al. [56] explore the connection between six air pollutants and the daily COVID-19 cases in China by employing a generalized additive model and find a significant correlation between air pollution and COVID-19 cases. Bashir et al. [52] analyze the relationship between COVID-19 and climate indicators in New York City by employing Kendall and Spearman rank correlation tests to confirm a significant association between air quality and COVID-19 outbreak. Studies have also reported the effect of Covid-19 lockdown on reduced levels of air pollution [39, 93,124].

4.2. Effect of land processes involving deforestation and latitudes in the spread of COVID-19 worldwide

The seasonality or the favorability of a pathogen to spread is based on the atmospheric season, which is observed in the case of many viruses [57]. For COVID-19 and other coronaviruses like SARS, similar seasonal variability is possible, as also evidenced by Sajadi et al. [125] and Tosepu et al. [67], where temperature and humidity have a consistent seasonal or respiratory virus distribution. Chen et al. [7] employ a meteorological model to analyze the correlation between the weather parameters and the spread of COVID-19 cases and predict a potential outbreak of an epidemic situation in high-latitude cities. Similarly, Poole [57] find a strong relationship between COVID-19 spread and environment temperature and latitude in the observed region of 25–55° North and 4–12° centigrade within the climatological band between December and February 2019–2020.

Deforestation is alternatively linked to various forms of disease outbreaks from bird and bat-borne viral conditions [126]. Minhas [127] argues that with over-population and economic development, people in India would need food and shelter, which shall directly or indirectly lead to deforestation, suggesting India to be the birthplace of the next outbreak. Hence, to prevent the outbreak of such a type, it is essential to understand the importance of forests and encourage afforestation worldwide [44]. Maithani et al. [117] reported an increase in hotspots and a reduction in thermal comfort index in the Indian city of Dehradun in their examination of land surface temperature during post the COVID-19 lockdown.

4.3. Effect of meteorological factors in the transmission of COVID-19 worldwide

The majority of the studies suggest meteorological conditions as one of the most important factors to forecast COVID 19 pandemic future patterns [60,128]. The meteorological factors include temperature, humidity, wind speed, visibility, and rainfall, which affect the survival of environmental viruses and further stimulate epidemic transmission [7]. Liu et al. [6] examine the link between novel COVID-19 case counts and meteorological factors in 30 cities of China and by applying a meta-analysis, their results confirm a positive transmission effect of the independent meteorological factors. By evaluating the effects of the weather parameters of nine cities in Turkey, Şahin [66] confirms the high correlation between wind speed and temperature and the spread of the COVID-19 disease.

Additionally, Chen et al. [7] examine the link between weather variables and the severity of outbreak in China, Italy, Japan and 51 other countries, indicating that combined temperature, wind speed and humidity can best predict infectious conditions. Similarly, Park et al. [129] examine the effects of temperature, moisture and diurnal temperature on pandemic incidence in temperate areas of Seoul, Korea and report substantial increases in the incidence of low and high moisture influences. Similar results revealing a significant relationship between temperature and humidity, and the transmissibility of the disease (COVID-19) is also evidenced by Bashir et al. [52] and Guo et al. [130] in New York City and Wuhan, respectively. Further, Tosepu et al. [67] explore the relationship between the meteorological factors and COVID-19 in Jakarta and opine a significant relationship between the spread of COVID-19 and temperature. Explicitly, temperature and humidity confirm to play a significant role in transmitting the disease [6].

The majority of studies have employed generalized additive modeling techniques to examine the interaction between meteorological factors and spread in COVID-19 cases. For instance, Qi et al. [131] and Shi et al. [71] analyze the influence of temperature and moisture on the COVID-19 pandemic dynamics in China, by employing the generalized additive model and the random-effect meta-analysis, respectively, to confirm a significant negative association between temperature and humidity and the COVID-19 cases. Ma et al. [128] explore the association between coronavirus disease deaths and weather parameters, using generalized additive modeling technique, and confirm that increase in temperature and humidity led to a decrease in the COVID-19 mortality rate.

In addition, while existing literature indicates an essential link in weather and COVID-19 cases, several studies contradict these findings and claim that temperature and moisture alone may not necessarily lead to a decrease in the number of cases [132,133]. Jamil et al. [134] explore the relationship between SARS-CoV-2 spread and temperature, across nations and Chinese provinces with at least 100 cases, and find no evidence that the rates of spread are falling at high temperatures implying that COVID-19 is unlikely to be a seasonal breathing virus. Gupta et al. [59] examine the role of weather conditions in spreading the COVID-19 disease in India and confirm that states with unhealthy weather conditions cannot be associated with the number of new cases in those regions.

Hence, with such contradicting results across the literature in this field. The impact of weather factors on COVID-19 distribution is understood ambiguously [46,59]. This gap highlights the need to investigate the combined effect of other factors such as demographic variables, infrastructure for healthcare sector, social policies like lockdowns, etc. to study such correlational observations.

4.4. Effect of non-meteorological factors in the spread of COVID-19 worldwide

To expand the validity and reliability of the results, numerous studies considered the meteorological and non-meteorological factors to

collectively study their impact on the spread of the COVID-19 disease. For instance, Briz-Redón and Serrano-Aroca [133] adopt a Spatio-temporary model for the investigation of the effect of temperature and non-meteorological factors like population density, population-by-age, number of travelers and business numbers on COVID-19 diffusion, and suggest that COVID-19 is higher among the people of a particular age group, as it affects older people more seriously and a greater number of active firms leading to intranational mobility. While evaluating the impact of temperature on the COVID-19 outbreak dynamics, Shi et al. [71] opine that environmental factors have a more significant impact on the causative virus than the host population, since it varies across different conditions. Population mobility and human-to-human contact are considered significant factors to predict the pandemic's future trend [94]. Jahangiri et al. [63] also examine the impact of temperature and population size on Iran's transmission rate of COVID-19 and recommend that cities with a population of over 1.7 million can track their management policies more strictly and accurately.

Iqbal et al. [75] report the connection between the environment, COVID-19 cases and the Chinese economy in Wuhan and the temperature insignificance in new COVID-19 diseases. The renminbi exchange rate shows a negative but minimal impact on China's export economy with the Wuhan COVID-19 outbreak. Further, Mollalo et al. [135] compiled 35 environmental, socio-economic, topographical and demographic variables to determine the spatial variability of the incidence of COVID-19 diseases, and the results show the mapping of the important explanatory variables (income inequalities, household incomes, black women's proportion and the percentage of nurse practitioners). Khurshid & Khan [136] study the impact of COVID-19 shock on the GDP, energy consumption and climate change, reporting the shortfall in GDP, low energy consumption and drop in average temperature.

Coronavirus transmission from contaminated surfaces has been assumed, stressing the importance of illustrating coronavirus persistence on inanimate surfaces [137,138]. Doremalen et al. [139] comparatively analyze SARS-CoV-2 and SARS-CoV-1 aerosol and surface stability, finding that SARS-CoV-2 transmission is accurate because the virus stays on the surfaces through the days of infection. Through the analysis of 22 studies, Kampf et al. [137] reveal that Middle East Respiratory Syndrome (MERS) coronavirus and Severe Acute Respiratory Syndrome (SARS) coronavirus can persist for up to 9 days on inanimate surfaces, but can be deactivated by surface disinfection [140,141].

4.5. Effect of water-based epidemiology in the spread of COVID-19 worldwide

With the publication of the first paper reporting the detection of SARS-CoV-2 in feces [142], it becomes clear than human wastewater might contain novel coronavirus [143]. Hence, it can be taken into consideration that symptomatic (and asymptomatic) affected people could spread the viruses through their excreta, which calls for a more effective waste-water and sewage-sludge treatment, and its subsequent spreading into the environment [144,145]. One of the main sources of human exposure to pollutants is through drinking water [140]. This directs the attention to some major contaminants in drinking water known to be immune-toxic and drinking water routes, which could possibly compromise the effective immune response of humans [146, 147].

While the unanticipated lockdown due to the spread of coronavirus affected the world's socio-economic development [148,149], there are also reports of reduced pollution levels as discussed in section 3.6. Wagh et al. [145] examine the lake water quality changes using two remote-sensing techniques and confirm an increase in spectral reflectance (SR) and Forel-Ule color Index (FUI), suggesting a reduction in water pollution. Similar positive results are concluded by Refs. [150, 151].

Wastewater-Based Epidemiology (WBE) is a new tool used to support

current monitoring systems for infectious diseases and an early warning system for disease outbreaks, which involves analyzing the pooled wastewater and contagious disease to monitor the emergence of a new disease outbreak efficiently [152]. With the economic and practical limitations of medical testing of COVID-19 worldwide, Hart & Halden [153] used computer analysis to assess local viability, opportunities and challenges of identified active coronaviral infections with WBE, and classify temperature, average time and water per capita as the key variables. Further, Mao et al. [154] suggest the paper-based device can detect SARS-CoV-2 in wastewater sites and track virus carriers. Ahmed et al. [156] emphasize the effectiveness of the WBE by detecting wastewater SARS-CoV-2 RNA in a sample in Australia and then estimate the number of people infected by Monte - Carlo simulation. Wastewater is also considered as an indirect effect of COVID-19 on the environment, for example, China calls for wastewater treatment plants to improve their routes of disinfection and prevent the spread of new coronaviruses to wastewater [111].

4.6. Environmental impact of COVID-19

The COVID-19 has caused considerable damage to public health and the economy worldwide. WHO announced a global public health emergency in January 2020 [157]. As of 23rd February 2021, the virus has spread to more than 112 million people and causing around 2 million deaths [158]. Subsequently, with the outbreak becoming a pandemic in the end of March, a nationwide lockdown took half the world's population, resulting into a worldwide shutdown of industrial activities [159]. Road and air transport stopped because people cannot travel [160]. However, reduced transport activities result in less energy consumption and lower oil demand, which leads to a significant positive impact on the environment [106]. Additionally, NO₂ (nitrogen oxide) is a dangerous pollutant, emitted especially from fossil fuel combustion, responsible for 350,000 new asthma cases per year in India [107]. However, due to quarantine, many countries, namely India, Italy, China, Spain, and France, have witnessed a significant decrease in the NO₂ concentrations [107,111].

Based on the recent data released by NASA (National Aeronautics and Space Administration) and ESA (European Space Agency), Muhammad et al. [106] indicate that air pollution in the epicenter of the COVID-19, such as Wuhan, Italy, Spain, and the USA, etc. has been reduced by 30%, suggesting it as a temporary advantage of the pandemic. Furthermore, Mandal et al. [161] suggest that positive changes in the air quality are observed due to the reduction in the concentration of PM₁₀, PM_{2.5}, CO₂, NO_x and other pollutants with the decrease in industrial activities, electricity demand, consumption of fossil fuels, road transport and the changes during the lockdown period. The governments must strategize on measures to reduce pollution post-COVID as well. Social distancing due to the pandemic outbreak has led to much cleaner beaches worldwide, including the ones in Mexico, Spain, Ecuador, etc. [111]. Similarly, the coronavirus disease has also caused a drop in water pollutants in some parts of the world; for instance, in Venice, since there is no tourist footfall, the Venice canals are relatively cleaner, and water pollutants dropped efficiently [109]. However, quarantine policies have led to increased waste, including medical waste. For instance, hospitals in Wuhan produce an average of 240 tons of medical waste per day due to the outbreak [111].

The pandemic has shifted the orientation towards a new model consisting of the digital economy, the knowledge economy, the sustainable economy, industry 4.0. with less effect on the environment on the one hand, while it has also demonstrated its hostile influence on human society [162]. Over the past few months, the outbreak has recovered the environment successfully with a positive effect on global climate change. It also stressed the need to improve the mutual harmony between humans and nature [44].

5. Future research agenda

This review highlights the relationship between different environmental factors and the transmission of SARS-CoV-2. We identify substantial evidence suggesting the role of (a) meteorological factors such as temperature, humidity, rainfall, wind [6,128,130,131], (b) air quality (quantity of aerosols and other air pollutants) [69,119,139,163], (c) non-meteorological factors like population density [31,164], number of travelers and number of companies, socio-economic factors [160, 165–168] and inanimate surfaces [133,139]. Researchers planning to undertake further studies in the field may consider environmental contamination, such as bowel shedding as an adjunct to the transmission of COVID-19 through the fecal-oral route [169]. Further, in this section, we discuss future directions based on themes and methodology (See Fig. 7).

It is important to note that the diseases like COVID-19 are transmitted from animals (zoonoses) to humans with further spread through human-to-human transmission, imposes a significant threat to ecosystem integrity and economic development. Though not much evidence is available yet about the direct transmission of the novel coronavirus from bats, yet the scenarios of recurrent encounters with bat CoVs, other animal viruses, and humans themselves allow a more significant threat in the future [126,170]. The sudden emergence of

COVID-19 pushes for scenario analysis of virus-related emergence events. The bat-borne novel coronavirus directs future researchers to work on awareness among people for the risks associated with anthropized environments. The spread of coronaviruses from multicellular to unicellular organisms, their multiplication, mutation, and transmission is another paramount concern for future researchers to address [144]. Currently, it is considered that COVID-19 can endure for just a few days out of the living cells like inanimate surfaces, but this time window can help it reach out to other living organisms, mutate and change traits. Therefore, the possible scenarios calling for researchers' attention in the future include understanding the underlying pathogenicity of COVID-19 and loopholes for its faster spread. These studies may help in setting up control measures for the aerial transmission of the virus. This further directs towards understanding the role of air on COVID-19 and how air density and air pollutants express and suppress its prevalence across the globe. The polluted air has a very negative impact on the biotic and abiotic components of the environment. Zhu et al. [56] prove an important link between air pollution and infection with SARS-CoV-2. This will lead to a future understanding of the origin of air pollution with SARS-CoV-2.

The age and gender-specific cases for identifying the combined effect of SARS-CoV-2 and air pollution, specifically on the vulnerable group (women, children, elderly, and immune-compromised), also call for

Thematic Propositions	
Transmission	<ol style="list-style-type: none"> 1. Spread from multicellular to unicellular organisms, their multiplication, mutation, and transmission 2. Risks associated with anthropized environments (animal-human interactions) 3. Understanding the pathogenicity of the virus and loopholes in its spread 4. Control measures for aerial transmission, including the need to explore the dynamics of SO₂, NO₂ and other aerosols in the spread of the disease
Socio-economic factors	<ol style="list-style-type: none"> 1. Age and gender specific cases for identifying the effect specially on vulnerable group (women, children, elderly and immune-compromised) 2. Lifestyle and behavioral adjustments affected with the outbreak of the pandemic 3. Research is needed to better categorise the impacts on urban and rural life, transport, work conditions and the populations physical and mental health 4. the outbreak has further widened the inequalities existing in the societies, which may further lead to economic crisis
Health Infrastructure	<ol style="list-style-type: none"> 1. Pandemic highlighted the need to boost the health-care sector 2. Mis-management of plastic and waste disposal has increased pollution, failing the sustainability targets 3. Need to develop efficient alert systems from an environmental health perspective 4. Need to identify and examine the risks associated with decisions taken to control the spread
Methodological Propositions	
	<ol style="list-style-type: none"> 1. Need to develop standard techniques for the detection and quantification of SARS- CoV-2 2. Need to develop the fecal-oral hypothesis as a transmission route of SARS-CoV-2 and identify other environmental routes for fecal to oral transmission in the present scenario 3. Need for experimental and observational studies to assess the effect of world climate in the long-run for anticipating pandemics 4. Experimental shreds of evidence are required to confirm the effectiveness of household filtration systems, chlorination, densification and boiling for the elimination of the novel virus 5. The underlying mechanism of propagation needs to be researched through in vitro methods. 6. Multi-disciplinary research across different disciplines including medicine, environmental sciences and engineering, anthropology, social sciences and behavioral economics to implement and validate models of emergence and transmission

Fig. 7. Future research agendas.

research attention. Zhu et al. [56] suggest that short-term exposure to higher SO₂ concentrations may reduce the risk of SARS-CoV-2. Hence, it becomes pertinent to explore the dynamics of SO₂ for a larger population from different parts of the world to assess decreased SARS-CoV-2 risk. Ogen [119] suggests that future studies shall undertake age, previous diseases, pre-exposure of Nitrogen dioxide (NO₂), and hypercytokinemia to measure the fatality rate due to COVID-19 wave. Further studies shall incorporate assessing aerosols and nitrogen dioxide as a measure along with carbon emission data to identify the transmission of COVID-19 pandemic and the effect of a decrease in pollution due to quarantine resulting in a lesser mortality rate [94,139,171].

For instance, Ahmadi et al. [68] identified that disease spread is higher in humid areas, and is slow in arid regions of Iran embarking the need for experimental and observational studies to assess the effect of world climate in the long-run for anticipating pandemics. The use of urban thermal variance index can be applied to different cities of India for assessing the thermal comfort level post-lockdown [117]. The varying climatic conditions from country-to-country need to be studied in addition to host behavior of the disease for a better understanding of the prevalence of novel coronavirus. It may be pointed here that SARS-CoV-2 is stable at 4° celsius and is stable on smooth surfaces and a pH of 4–10 but is vulnerable to various disinfectant methods. Hence, the underlying mechanism of propagation needs to be researched through in vitro methods. Apart from this, Qi et al. [131] reported the effect of meteorological factors like temperature and humidity on COVID-19 with spatial and temporal variedness in mainland China, and it could be drawn from their work that such study needs to be pursued in the global scenario.

Additionally, the methodological perspective proposes the development of the fecal-oral hypothesis as a transmission route of SARS-CoV-2 and unzipping other environmental routes for fecal to oral transmission in the present scenario. Since viral titer in fecal loads is present in wastewater, wastewater-based epidemiology can be predicted through RT-qPCR, while more longitudinal studies are required for a given population. Furthermore, there is a need to study indoor versus outdoor transmission rates as the virus may get circulated through the exchange of airflow through an indoor ventilation system and air sampling for viral activities can be done. In vivo, however, actual patient cough, sneeze, breath aerosols should be done to understand the possibility of SARS-CoV-2 nosocomial spreading. The transmission of SARS-CoV-2 should also be checked by the PPEs. There is a need to develop standard techniques for detecting and quantifying SARS-CoV-2 in the water phase assessment of favorable environments for its survival and decay in water; and developing effective strategies for eliminating the novel virus from water. Furthermore, it is imperative to understand the mechanism of virus survival and develop low-cost, user-friendly techniques to eradicate coronavirus. The use of time series modeling via deep learning for studying variables such as climatic indicators and population density, public health policies, political and social structures, healthcare quality, intervention for healthcare facilities, global connectedness are useful in forecasting the course and spread of SARS-CoV-2. Future studies may also incorporate confounding factors such as human behavior, demographic variations, healthcare infrastructure, and social policies like lockdowns to study transmission dynamics [133]. Wang and Su [110] suggest working on the development of theory mainly representative of the emergency-economy-environment aspect to bring in a common junction point across the globe in the present COVID-19 pandemic. Progress in these research avenues would help manage similar pandemics in the future and safeguard human health and the environment.

6. Conclusion

We performed the thematic analysis and bibliometric review of 328 research papers on the transmission of novel coronavirus in various environmental types and synthesized the evidence regarding the

environmental concerns of COVID-19. The significant presence of viral loads in the environment by SARS-CoV-2 patients suggests how the environment acts as a medium for its transmission. Our analysis provides preliminary results supporting temperature being a driver of COVID-19, but not necessarily the only one [69]. The speed of transmission of the novel coronavirus is negatively correlated to temperature and humidity, and some evidence is available to support that the spread of COVID-19 can stop in warmer conditions [130]. Conversely, some literature also suggests the lack of evidence for a decrease in COVID-19 cases at warmer temperatures [134]. Hence, the combined effect of temperature, wind speed, and relative humidity may help in predicting the pandemic, and the meteorological model could forecast a high correlation with the real data. In addition to the climatic factors, the studies also incorporate other socio-ecological factors, namely, deforestation, population size, socio-economic development [172], and urbanization, while modeling the transmission of COVID-19. The human population is increasing, causing pressure on land use, agriculture and deforestation. As land usage rises, bat populations settle in areas closer to human homes, causing flea viruses [44,126]. Deforestation and anthropization on the bat-borne diseases call for working on the education and awareness among masses, regarding the risks associated with anthropized environments [22,173,174]. Moreover, while SARS-CoV-2 transmission through human respiratory droplet and direct contact is evident, there is a misunderstanding of the potential for aerosol transmission, suggesting future scholarship to explore the aerosol virus infectivity.

The mainstream literature focuses on few of the highly infected nations including China, Singapore, USA, Iran, Brazil, and India. However, other highly infected nations, including Russia, Spain, France, Italy, Germany, and many more, are equally relevant and may assist in developing appropriate diagnostics, therapeutics, vaccines, containment measures, and clinical management procedures [164,175,176].

Our study of the methods used in the papers under review coupled with the methods of the studies from the previous disasters leads us to observe that the survival of the COVID-19 virus in different environmental media needs high sensitivity models for precise quantitation of the SARS-CoV-2. Air Quality Dispersion Modelling System (AERMOD), sensitivity analysis, mathematical models created with Systems Dynamics methodology, the time-series modeling techniques using statistical tools (Generalized Additive Model (GAM) or the Wavelet Transform Coherence (WTC) or the non-linear regression tests) may be employed to study the nexus between COVID-19 cases and the environmental factors (such as temperature, wind speed, air-pollutants, water-based epidemiology, land, and in-animate surfaces). Future researchers may also consider case-control approaches to identify critical transmission risks in a particular setting or community (such as hospitals, care settings, or workplaces), by conducting multidisciplinary integrated studies of empirical and molecular epidemiological approaches.

Public health infrastructure is the most prominent measure to contain the spread of any pandemic. So far, not much of the literature has dealt with the success of public health [177] infection prevention and control measures (IPC) for the management of COVID-19 transmission during the current outbreak. Literature on the modes of COVID-19 virus transmission from clinical samples [51,178,179], can further assist in identifying priority IPC measures in preventing and reducing the transmission of the pandemic. Literature observes that the monitoring clinics and laboratories for providing information on public health and upcoming potential hazards are not sufficient [152]. Therefore, there is a need for a surveillance technique to monitor environmental exposure providing comprehensive exposure status and disease outcomes.

COVID-19 is a global threat demanding a country-wide response, calling on global scientists, policymakers, and collaborators to rapidly broaden research on the virus and monitor its spread and virulence. The integration of research activities and lessons learned from the previous pandemic outbreaks, including SARS, Ebola, Lassa fever, and Nipah, has

led to prompt research response [180]. Future researchers and experts would do well to make concerted efforts to support the ongoing or future outbreaks worldwide to sustain this capacity.

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Declaration of competing interest

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

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Appendix A. Supplementary data

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