



A bibliometric analysis of the impact of COVID-19 social lockdowns on air quality: research trends and future directions

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Abstract

Social lockdowns improved air quality during the COVID-19 pandemic. Governments had previously spent a lot of money addressing air pollution without success. This bibliometric study measured the influence of COVID-19 social lockdowns on air pollution, identified emerging issues, and discussed future perspectives. The researchers examined the contributions of countries, authors, and most productive journals to COVID-19 and air pollution research from January 1, 2020, to September 12, 2022, from the Web of Sciences Core Collection (WoS). The results showed that (a) publications on the COVID-19 pandemic and air pollution were 504 (research articles) with 7495 citations, (b) China ranked first in the number of publications ($n = 151$; 29.96% of the global output) and was the main country in international cooperation network, followed by India ($n = 101$; 20.04% of the total articles) and the USA ($n = 41$; 8.13% of the global output). Air pollution plagues China, India, and the USA, calling for many studies. After a high spike in 2020, research published in 2021 declined in 2022. The author's keywords have focused on “COVID-19,” “air pollution,” “lockdown,” and “PM_{2.5}.” These keywords suggest that research in this area is focused on understanding the health impacts of air pollution, developing policies to address air pollution, and improving air quality monitoring. The COVID-19 social lockdown served as a specified procedure to reduce air pollution in these countries. However, this paper provides practical recommendations for future research and a model for environmental and health scientists to examine the likely impact of COVID-19 social lockdowns on urban air pollution.

Keywords COVID-19 · Social lockdowns · Air pollution · Bibliometric analysis · Citation analysis

Introduction

On December 31, 2019, the world experienced a novel virus that caused animals and humans to be sick. Shortly after it broke out, the World Health Organization (WHO) declared it a pandemic and named it SARS-COV-2 and the disease COVID-19 (Gautam 2020; Pei et al. 2020). On February 11, 2020, WHO termed the disease as COVID-19. The name was formed from CO stands for “Corona,” VI stands

for “Virus,” and D stands for “Disease” (Chakraborty and Maity 2020). World history documents several pandemics that have hit the world, like the plague, smallpox, measles, cholera, influenza, Ebola, human immune virus (HIV)/acquired immune deficiency syndrome, severe acute respiratory syndrome (SARS), and now COVID-19.

As of the time this paper was written, 203,295,170 COVID-19 cases had been confirmed, including 4,303,515 deaths globally (World Meters Info 2022). The consequence of the virus infection is a severe lung injury and respiratory pain disorder that eventually causes pulmonary failure and causes death. The virus of COVID-19 is spread through contact with respiratory droplets instead of air. Generally, the virus spreads very fast, and the main way of spreading is through respiratory drops given off by a person suffering from a cold and cough (Aboagye et al. 2022; Xie and Chen 2020). People who contract this deadly virus show at least some of these symptoms: dry cough, fever, and difficulty breathing. Children, older people, and those with health complications like high blood pressure

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(B.P.), cancer, diabetes, heart problem, and asthma are more prone to develop this disease (Chakraborty and Maity 2020; Dong et al. 2020). Experts advise everyone to maintain a 1-m social distance, especially away from infected people (Schormans et al. 2021).

Social lockdowns have been considered an effective control measure for fighting the COVID-19 menace (Adam et al. 2021; Arora et al. 2020). Since various governments adopted social lockdowns, it was realized, especially in the first three months, that air pollution had declined. Hence, experts and researchers could conclude that there was a “fortune amidst the misfortune” (Aboagye et al. 2021; Cheval et al. 2020; Desouza et al. 2021). Based on this, the social lockdown became predominant in reducing the transmission of COVID-19, thereby halting most industrial activities, transportation, and human mobility. Industries classified as essential are allowed to operate (Muhammad et al. 2020).

Consequently, this has impacted Outdoor Air Quality (OAQ) since there have been many improvements in many parts of the world because the emissions of major air pollutants from major sources, such as vehicular traffic and industries, halted mortalities (Adam et al. 2021; Naqvi et al. 2021). This reflection implies that air pollution can directly affect economic growth and human activities (Jin et al. 2016; Liu et al. 2021). Globally, due to the restrictions placed on industrial and human mobility, air quality has improved to 66% (Sathe et al. 2021; Yadav et al. 2020). Since COVID-19, several global experiments have improved our understanding of air pollution, air quality concerns, and their effects. These scientific results that have been concluded will serve as a source and basis for formulating and enacting environmental laws and policies to improve air quality (Marinello et al. 2021; Mehmood et al. 2022; Zangari et al. 2020). During the lockdown, numerous cities reported lower atmospheric concentrations of key air pollutants like particulate matter (PM; PM_{10} and $PM_{2.5}$), nitrogen dioxide (NO_2), carbon monoxide (CO), sulfur dioxide (SO_2), and ozone (O_3) (Filonchik et al. 2020; Filonchik and Peterson 2020).

Some researchers have explored several researches with different methods to find the impact of COVID-19 social lockdowns on air quality (see Table 1). Although the current study attempts to emphasize global COVID-19 social lockdowns and improved air quality, it contributes considerably to the literature in other ways than previous studies (Table 1). The researchers adopt a bibliometric analysis to assess the global impacts of COVID-19 social lockdowns on air quality from January 2020 to September 2022. Thus, the current study aims to offer a straightforward analysis of the evolution of published articles on COVID-19 social lockdowns on air quality as well as emerging benefits and challenges of COVID-19 social lockdowns on air quality while discussing the future research areas of COVID-19

social lockdowns on air quality. The study pursues the following objectives explicitly:

- (a) To assess the suitability and quality of the subject area through the identification of leading authors, patterns, and performances of countries or institutions;
- (b) To examine collaborations among institutions and countries that have enormously contributed to research in the field of COVID-19 social lockdowns on air quality research to unearth the research evolution between countries, and
- (c) To find out present hotspots in this knowledge domain based on keyword analysis which may impact and through more light on the possibilities for future research in the field.

Explicitly, this research answers the following outlined research questions:

- (1) What is the developing trend in this research field?
- (2) Which journals, subject categories, institutions, and regions involved in COVID-19 social lockdowns on air quality are prevalent?
- (3) Who are the most influential authors, and what are their collaborations with COVID-19 social lockdowns on air quality?
- (4) What are the current research’s authorship output, citation, and co-citation structure?
- (5) What are the prevalent developing themes in COVID-19 social lockdowns on air quality research and areas that need further studies?

The current study’s findings provide practical recommendations for future research and offer a model for environmental and health scientists to examine the potential impact of the COVID-19 social lockdowns on urban air pollution.

The change in air quality has been studied based on measurements of these criteria air pollutants at regular fixed monitoring stations and satellite-based observations (Aboagye et al. 2021; Alvarez et al. 2020; Desouza et al. 2021; Fuwape et al. 2021; Smith et al. 2020; Venter and Louren 2021). On the contrary, not all cities experience an outright improvement in air quality. In this period, some countries experienced worse air pollution, thus observing a worsening air quality. These variations in experimental data might be due to variations in meteorological factors or the role of atmospheric interaction while having clear skies. For instance, the surface levels of O_3 , a secondary air pollutant, have frequently been reported to be stable or even increasing (Liu et al. 2021; Zoran et al. 2020). These unexpected findings should be studied to improve our understanding of secondary air pollutants, their movement and

Table 1 Comparison of previous studies of COVID-19 social lockdown and air-quality

Author	Article title	Time period	Keywords	Focus of study	Methodology	Findings
Casado-Aranda and S'anchez-Fern'andez (2021)	Analysis of the scientific production of the effect of COVID-19 on the environment: A bibliometric study	December 2019 to September 2020	Environmental studies, Bibliometric analysis, SciMAT, COVID-19, Coronavirus	Analyzed 440 articles to explore the relationship between the effect of the COVID-19 pandemic on the food supply chain and waste habits actions to mitigate climate change	Bibliometric analysis	The findings of the study revealed that the scientific production related to the topic of COVID-19, and the environment has increased significantly since the beginning of the pandemic. The study also found that the most researched areas were air pollution and the impact of the pandemic on greenhouse gas emissions.
Bao and Zhang (2020)	Does lockdown reduce air pollution? Evidence from 44 cities in northern China	Between 1 January and 21 March 2020	Travel restriction, Air pollution, Human mobility, Dynamic panel Covid-19	Expounded on the impact of COVID-19 on the reduction in pollution in 44 cities in northern China	Survey	Their study showed that a decline in air pollution positively correlated with travel restrictions.
Jain and Sharma (2020)	Social and travel lockdown impact considering coronavirus disease (COVID-19) on air quality in Megacities of India: present benefits, future challenges and way forward	-	Interpolation technique, Arc GIS, Air quality, Vulnerability, Environmental health	To assess the overall impact of social and travel lockdown in five megacities of India; Delhi, Mumbai, Chennai, Kolkata, and Bangalore. The study evaluated the spatiotemporal variations in five criteria pollutants over two time periods	Survey	Revealed that the concentration of PM _{2.5} , PM ₁₀ , NO ₂ , and CO declined by ~41% (66–39 µg m ⁻³), ~52% (153–73 µg m ⁻³), ~51% (39–19 µg m ⁻³), and ~28% (0.9–0.65 mg m ⁻³) during the lockdown phase in comparison to the before lockdown in Delhi, respectively
Aboagye et al. (2021)	"Fortune amidst misfortune": the impact of COVID-19 city lockdowns on air quality	2020	Air pollution, air quality, COVID-19, Coronavirus, CO, SO ₂ , NO ₂	To unravel how air pollution intensified COVID-19-associated mortality or morbidity in China, Italy, and the USA.	Observation/evidence captured by Sentinel-5 satellite	In a related study, the researchers found that exposure to long-term air pollutants (PM ₁₀ , PM _{2.5} , NO ₂ , and O ₃) was positively correlated with COVID-19 cases
Bhatti et al. (2022)	Air pollution; air quality; COVID-19; coronavirus; CO; SO ₂ ; NO ₂	-	Air pollution, COVID-19, Particulate matter, China	This study investigates the change in air pollution (focusing on the Air Quality Index (AQI))	Trajectory analysis	Although the COVID-19 pandemic had numerous negative effects on human health and the global economy, the reduction in air pollution and significant improvement in ambient air quality likely had substantial short-term health benefits; the government must implement policies to control post-COVID environmental issue
(Aamir et al. 2021)	Spatiotemporal change of air-quality patterns in Hubei province—a pre-to post-COVID-19 analysis using path analysis and regression	2019 to 2021	air pollution, COVID-19, particulate matter, China	To study the impact of the strict control measures of the new COVID-19 epidemic on the air quality of Hubei in early 2020	Survey	Although the COVID-19 pandemic had numerous negative effects on human health and the global economy, it is likely that the reduction in air pollution and the significant improvement in ambient air quality due to lockdowns provided substantial short-term health benefits

Table 1 (continued)

Author	Article title	Time period	Keywords	Focus of study	Methodology	Findings
Hasnain et al. (2022)	Time series analysis and forecasting of air pollutants based on prophet forecasting model in Jiangsu province, China	2022	prophet forecasting model, time series model, air pollution, machine learning, Jiangsu province, China	The current study aimed to predict both short-term and long-term air pollution in Jiangsu province, China, based on the prophet forecasting model (PFM). We	Survey	PFM has extensive power to accurately predict the concentrations of air pollutants and can be used to forecast air pollution in other regions.
Present Study	A bibliometric analysis of the impact of COVID-19 social lockdowns on air quality: research trends and future directions	2020 and 2022	Covid-19, social lockdowns, air pollution, bibliometric analysis, citation analysis	This research adopted the bibliometric approach from a global perspective to measure the impact of COVID-19 social lockdowns on air pollution while identifying the evolving problems and discussing the future viewpoints during the ongoing COVID-19 pandemic.	Bibliometric analysis	Air pollution plagues China, India, and the USA, prompting many studies. After a high spike in 2020, research published in 2021 declined in 2022. Authors keywords have focused on "COVID-19," "air pollution," "lockdown," and "PM _{2.5} ." These keywords suggest that research in this area is focused on understanding the health impacts of air pollution, developing policies to address air pollution, and improving air quality monitoring.

NB: comparison of previous studies of COVID-19 social lockdown and air quality and the present study

evolution under diverse meteorological circumstances, their health effects, and current air pollution management methods. The social lockdown intervention that various governments implemented suggested that people stay home, thus spending their time in their indoor environment. As a result, PM and Volatile Organic Compound (VOC) emissions from day-to-day activities such as cooking, cleaning, and smoking can expose indoor dwellers to toxic air pollutants (Pei et al. 2020).

In making a review study, bibliometric analysis has proven to be an effective and most widely scientific research approach, adopted in many fields of study. It helps disciplines to determine the structure and characteristics of a field of study by mapping the distribution, scalar relationship, and change regulation of literature and information (Mao et al. 2015). Recently, many researchers have adopted a bibliometric approach and other review approaches in COVID-19 lockdowns and improvements in air quality and food supply chain research. Researchers must be able to expound on and describe the exact situation in current review research, hot topical issues, trends in future research fields in COVID-19, and social lockdown on air pollution. This could be done through critical surveying and summarizing related literature; nonetheless, the researchers found that there is little research that focuses on COVID-19 and social lockdown on air pollution via a bibliometric approach. Based on the Web of Science Core Collection (WoS), several scholars have contributed to COVID-19 social lockdowns and air quality in diverse ways. This has been summarized in Table 1.

Materials and methods

Data sources

The bibliometric analysis uses scientific, arithmetic, and statistical approaches to investigate the document structure types, features, and forms by taking documents as the research object. The researchers gathered data for this study through the Core Collection of Web of Science (WoS) collected by Thomas Reuters and jointly integrated into the ISI Web of Knowledge. WoS is a generally adopted catalog that gives statistics on document types, language, countries/regions, institutions and authors, funding agencies, journals, and subject groups and types. WoS allow the researcher(s) to download all records and cited references of articles published in .txt format. The researcher(s) can use the .txt to generate maps and analyze data in other software. For this review article, the researchers downloaded academic publications on the impacts of COVID-19 social lockdowns on air pollution from the WoS database on September 12, 2022.

The search terms for this review article were TOPIC: (“corona virus lockdown*” OR “Covid-19 lockdown*” OR “covid 19 lockdown*” OR “coronavirus lockdown*” (Topic) and “air quality” OR “low air pollution”) set to a timespan of January 01, 2020–September 12, 2022. The search generated 517 documents, further filtered by the researchers based on document type and language. Hence, the final document used for further analysis was 504. Figure 1 is the flowchart of data analysis procedures employed in the study.

Analyzing data using CiteSpace software

CiteSpace is among the commonly used tools for imagery and visualization in scientific research (Chen 2006a, Chen et al. 2010). The CiteSpace software is an open-source Java application that cites and classifies information on related literature and continues to produce a graphic representation of the data generated (Chen et al. 2014a). Two components make up CiteSpace’s visualization and mappings, thus, nodes and links. The nodes represent authors, institutions, countries/regions, journals, keywords, subject groupings, and cited references. At the same time, links replicate the co-occurrence or co-citation association between nodes (Chen et al. 2014b). The physical characteristics of the nodes are such that they usually define the evolution and growth of a research domain.

The researchers analyzed the general characteristics of academic research published on COVID-19 and air quality, conducting a collaboration analysis to plot the cooperation links between authors and countries in this area. To give more understanding of the academic structure of the research area, the researchers continued to conduct co-citation of the documents and journals. CiteSpace was then used to track COVID-19 social lockdowns and air quality research by identifying and cataloging key research areas, development, and current status. Zhang et al. (2020a) suggest that CiteSpace parameters, such as time slice, node type, and pruning, must be thoroughly checked and selected in concinnity with the study’s objectives. In this regard, the researchers set the study parameters to (a) time slicing: 2020–2022; (b) years per slice: 1; (c) node type: country, author, keyword, and cited journal; (d) network selection criteria based on top $N = 50$; (e) link strength and scope: cosine and within slices, respectively.

The measure of influence: h-index and impact factor

For the researchers to best measure the cumulative impact and significance of an individual’s scientific output with the advantage of being unbiased, the researchers adopted the *h*-index as proposed by Hirsch in 2005 (Hirsch 2005).

In this vein, one is associated with a particular article published and may be an author, country, or journal. Brandão and Soares de Mello (2019) add that the h -index is linked to a particular period that the h papers from an individual have been cited at least h times. Hence, the researchers used this index based on the total number of citations and publications in this study. Impact factor (IF) is another significant performance indicator widely used to assess the quality of journals. IF represents the source's mean citations metric of journal articles published over 2 years (Ma et al. 2018). The researchers, therefore, obtained the IF of top-performing journals from the Citation Reports (JCR) 2019 edition.

Results and discussion

The characteristic of scientific production

Of the 504 documents, original articles of 484 took the leading number of retrieved publications and constituted 96.03% of the total, while articles with early access constituted 20 of the entire documents and represented 3.97% (Table 2). The trends in the number of publications and citations are presented in Fig. 2. Generally, between 2020 and 2022, there were several publications. However, there were fluctuations in the number of publications. It could be realized that there was a quick rise in publications from 2020 to 2021. Thus, there was a significant increase in the number of publications in this period. Also, there was a sharp decrease in publications from 2021 to 2022, mainly because our study did not cover the entire 2022. By the end of the year, additional publications will plausibly increase the total number of publications in 2022. Citations also took

a similar trend as the number of publications. The year 2021 recorded the highest citations. There was a sharp increase from 2020 to 2021, but those recorded in 2022 were lesser than in 2022. The 504 and have been cited 7495 times. Moreover, the vast number of citations between 2020 and 2021 may be associated with the sharply increased number of articles published between the periods. Essentially, research on the COVID-19 lockdown and its effects on air pollution is still beginning and has received many scholarly citations.

Based on the document content analysis, there were 919 total keyword plus (ID) and 1054 author keywords (DE). Also, the study recorded 2607 author appearances, 12 single-author documents, and 2595 multi-authored documents. It was realized that this study's co-author per document and international co-authorship were 6.43 and 39.88, respectively (Table 2). This indicates that many authors participated in the COVID-19 social lockdown and air pollution, underscoring this research theme's significance.

Scientific collaboration between countries

The scientific collaboration of different categories was also assessed based on the affiliation of at least one article author. Overall, some authors from 57 countries contributed to articles regarding COVID-19 social lockdowns and air pollution. Table 3 presents the first 20 most productive countries where these authors who have contributed to these discussions are affiliated, consisting of nine countries from Europe, six countries from Asia, four countries from America, and one from Australia. China was ranked first based on its document output of 151, which constitutes 29.96% of the total output and has the highest citations, similar to the study by Mehmood et al. (2022). This shows

Fig. 1 Flow chart of bibliometric analysis on COVID-19 and air quality research from 2020 to 2022

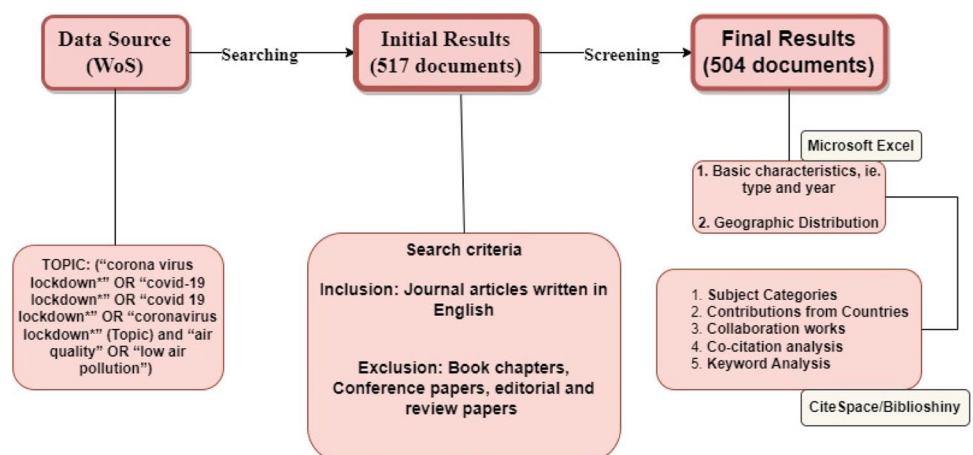


Table 2 Basic information on scientific publications used in this study

Description	Results
Main information about the data	
Timespan	2020:2022
Sources (journals)	138
Documents	504
Average citations per doc	14.8
References	15,322
Authors	
Authors	2607
Authors of single-authored docs	12
Document contents	
Keyword plus (ID)	919
Author's keywords (DE)	1054
Authors collaboration	
Single-authored docs	13
Co-authors per doc	6.43
International co-authorships %	39.88
Document types	
Article	484
Article; early access	20

that China is the first country to introduce research on the theme related to the impact of COVID-19 social lockdowns on air pollution.

The single country publication (SCP) and multiple country publications (MCP) were 94 and 57, respectively, with a 0.337 MCP ratio (Table 2). India came up second with 101 documents representing 20.04% of the total output. India also recorded SCP and MCP of 72 and 29,

respectively, with an MCP ratio of 0.287 (Table 2). The USA was ranked third with 41 documents representing 8.13% of the total output and recorded SCP of 14 and MCP of 27 with an MCP ratio of 0.659. By qualitative inferences, articles from China, India, and the USA have gained 3228, 1092, and 1684, respectively. Figure 3 demonstrates the geographical dissemination of all countries involved in this study's subject research. Based on the study's timeline, the initial countries in this field are China, India, and the USA, with publications from 2020. Most of the remaining countries started producing publications in 2021. Figure 4 shows the collaboration network of countries with more than ten publications. The network consisted of 76 nodes with 112 links. The network density of 0.0393 indicates that the countries' connections are moderately tight. It was noted that the countries with the most published articles have a closer relationship. China, New Zealand, England, and the Netherlands were key nodes in connecting groups of large nodes due to their high centrality of 0.45, 0.43, 0.28, and 0.26, respectively.

Altogether, China, India, and the USA have contributed positively to the COVID-19 social lockdown and air quality research. This has been so as several scholars (Bao and Zhang 2020; He et al. 2020) assert that the COVID-19 pandemic first emerged in Wuhan, China, and quickly spread worldwide. From a country-level perspective, China, India, and the USA were the leading countries working on COVID-19 and air pollution research. In contrast, England, France, Italy, Germany, and Switzerland contributed positively to this discourse. It can also be identified in Table 2 that, aside from China and India, most of the productive countries are based in Europe. This can be associated with the high collaborative network among European countries.

Fig. 2 Annual distribution of publications and citations

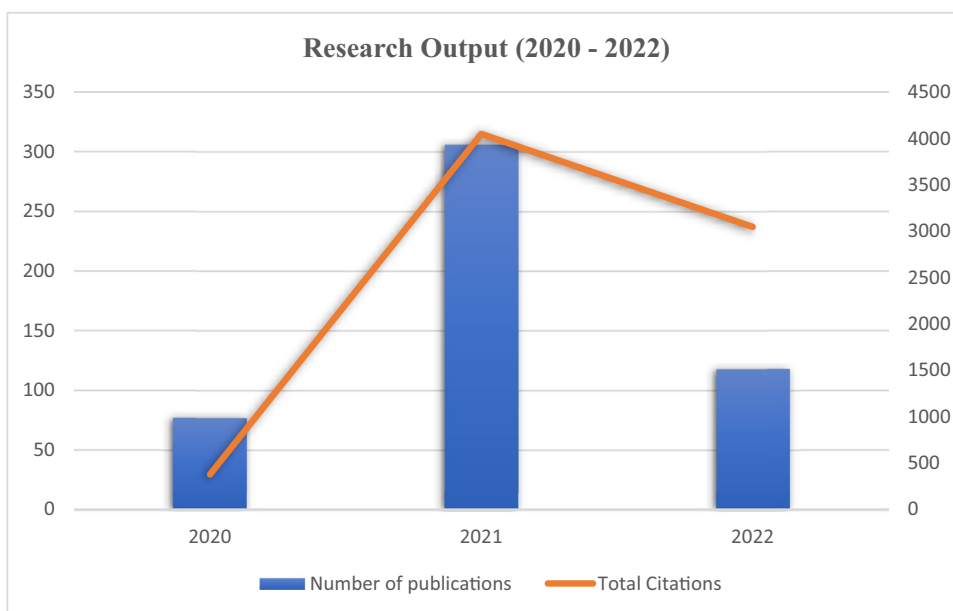


Table 3 Countries' scientific productivity

Country	NP	SCP	MCP	F	MCP_ratio
China	151	94	57	0.3	0.377
India	101	72	29	0.2	0.287
USA	41	14	27	0.081	0.659
Italy	25	18	7	0.05	0.28
UK	22	12	10	0.044	0.455
Spain	18	17	1	0.036	0.056
Canada	8	5	3	0.016	0.375
Germany	8	3	5	0.016	0.625
Australia	7	2	5	0.014	0.714
Kazakhstan	7	4	3	0.014	0.429
Saudi Arabia	7	5	2	0.014	0.286
France	6	3	3	0.012	0.5
Greece	6	1	5	0.012	0.833
Poland	6	6	0	0.012	0
Malaysia	5	1	4	0.01	0.8
Turkey	5	5	0	0.01	0
Mexico	4	3	1	0.008	0.25
Norway	4	1	3	0.008	0.75
United Arab Emirates	4	1	3	0.008	0.75
Argentina	3	1	2	0.006	0.667

NP, number of publications; F, frequency; SCP, single-country publications; MCP, multiple country publications

Most productive journals and journal co-citation analysis

This section of the paper expounds on active journal analysis, which aids research scholars in understanding how articles related to COVID-19 social lockdowns are distributed across journals while selecting the top journals to publish their related research works. The 504 documents retrieved for this study regarding the impact of COVID-19 social lockdowns from 2020 to 2022 were published in 138 journals. Twelve (8.69%) comprised ten or more published articles. Table 4 presents the performance of the top 20 most productive journals, representing 54.76% of the total document. The two most productive journals with regards to the number of publications and *h*-index were Atmosphere (IF 2021, 3.110; NP = 38, 7.54%) and Science of the Total Environment (IF 2021 = 10.753; NP = 37, 7.34%); however, Atmosphere and Science of the Total Environment are ranked 20th in terms of IF. Despite being ranked 19th in terms of the number of articles published (IF 2021 = 11.558; NP = 6, 1.19%), Environmental Science & Technology Letters was the most productive journal in terms of IF and placed 12th in terms of citations. This shows the quality of articles published in this journal.

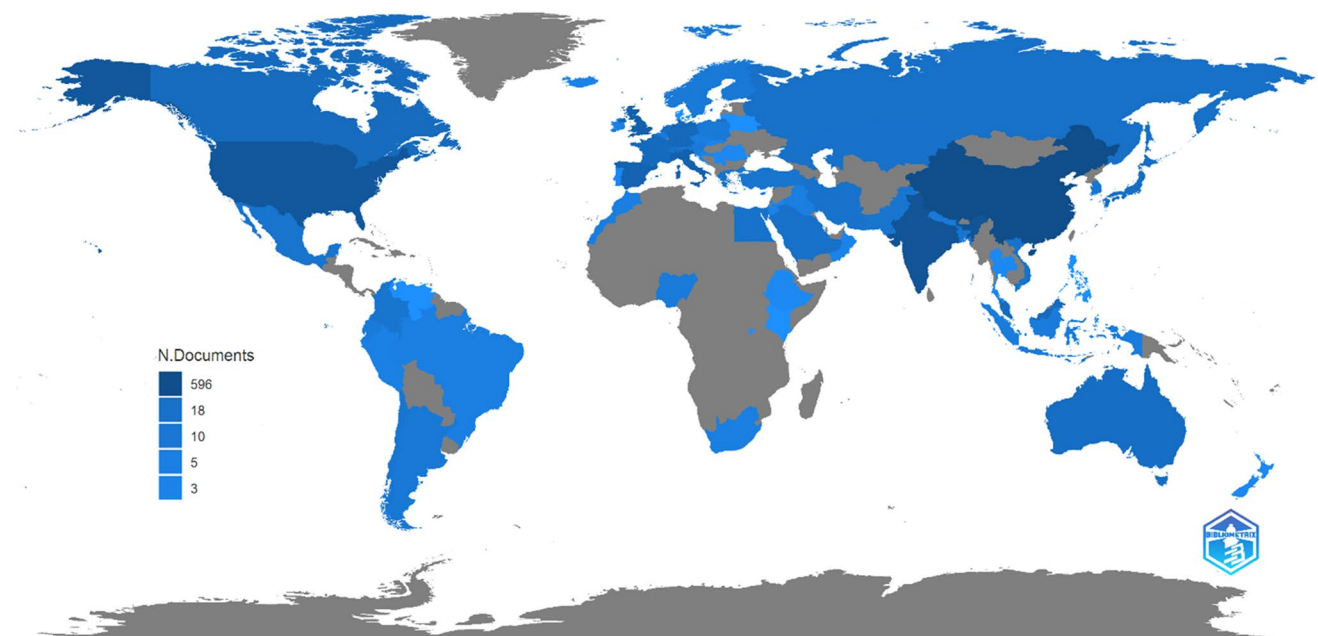
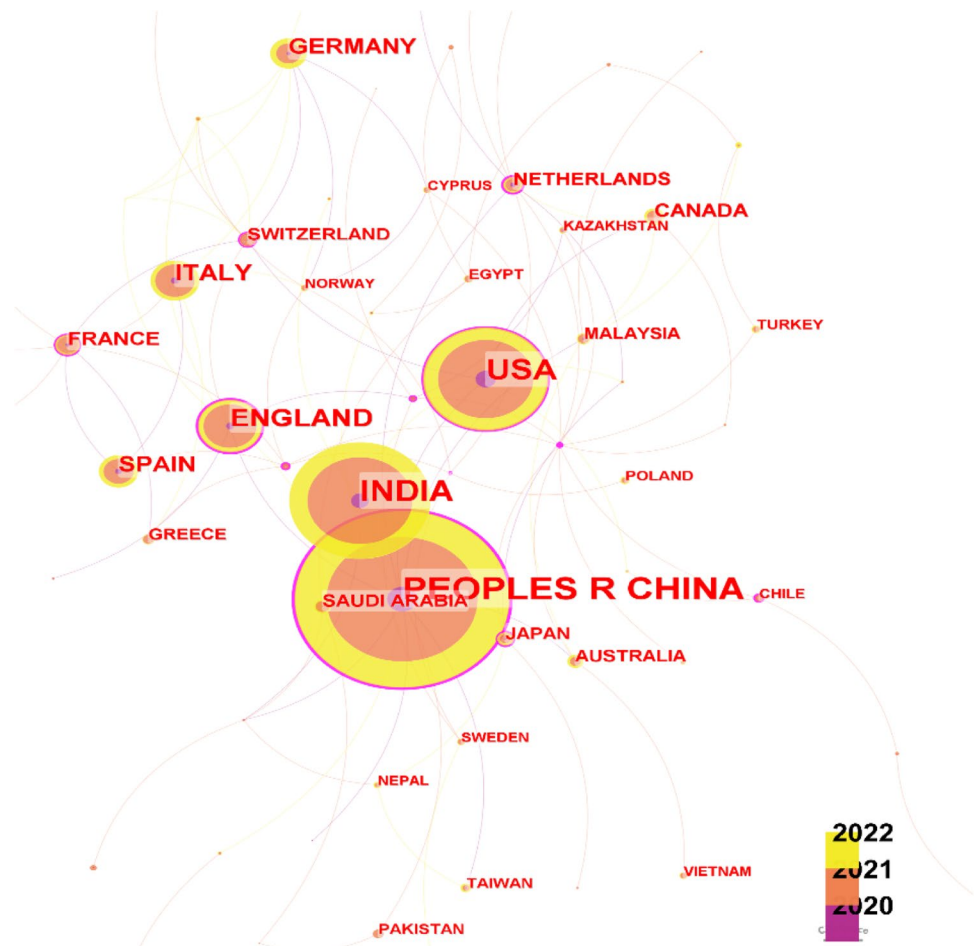


Fig. 3 Global distribution of all countries/regions that have conducted studies on the impact of COVID-19 social lockdowns and air quality between 2020 and 2022

Fig. 4 Academic collaboration among the most productive countries. Note: purple rings represent the degree of centrality; node size depicts the frequency of publications



The most productive journals based on IF, especially *Science of the Total Environment*, *Environmental Science & Technology Letters*, *Journal of Cleaner Production*, and *Environmental Pollution* (Table 4) in this research field are usually interdisciplinary, encapsulating the total environment that interfaces the biosphere, atmosphere, lithosphere and anthroposphere, air quality, global change, effects on the environment, environmental health sciences, and public health.

Journal co-citation analysis refers to when the same paper cites two journals (Afrane et al. 2022a, b). Figure 5 displays the co-citation link of the most productive journals. The network comprises a total of 67 nodes and 70 links. Minor journals seemed unlabeled in the network because they did not meet the set threshold for the analysis. The three journals with the most co-citations were *Science of the Total Environment*, *Atmosphere*, and *Environmental Pollution*, with co-citation frequencies of 434, 360, and 315, respectively.

Author analysis and highly impactful work

This section of the research presents the performance of the top 10 authors leading the research on the impact of

COVID-19 social lockdown and air pollution. The scientific community has a vital role in research improvements, and their published research output indicates the level of their analysis. Besides, the co-citation and citation connections illustrate the metrics of the researcher and aid researchers in understanding the implication of the research work on this theme. Table 5 displays this group of authors, constituting 0.38% of the total authors participating in the current study. However, their publications represent 14.68% of the total publications retrieved for this study. According to the number of publications, Wang Y., Li L., Wang H.L., Kumar S., and Liao H. were the top 5 publishing authors and emerged first based on *h*-index rankings. Furthermore, Fu Q.Y. is the most globally cited author.

In addition, the academic co-authorship among influential authors was analyzed and displayed in Fig. 6. Figure 6 shows that Shi et al. (2021) have collaborated to publish an article in *Science Advances* on “Abrupt but smaller than expected changes in surface air quality attributable to COVID-19 lockdowns.” In this paper, the authors unraveled and concluded on the need for sophisticated analysis to quantify the air quality impacts of interventions and

Table 4 Journal metric analysis related to the impact of the COVID-19 pandemic lockdowns and air pollution

Element	H_index	G_index	M_index	TC	NP	IF
Science of the Total Environment	16	37	5.333	1741	37	10.753
Aerosol and Air Quality Research	10	20	3.333	454	32	4.530
Atmosphere	10	15	3.333	271	38	3.110
Atmospheric Chemistry and Physics	9	16	3	265	23	7.197
Environmental Pollution	9	16	4.5	279	26	9.988
Geophysical Research Letters	9	17	3	385	17	5.576
Environmental Research	8	13	4	170	16	8.431
Remote Sensing	8	12	2.667	157	17	5.349
Air Quality Atmosphere and Health	6	10	-	204	10	5.804
Environmental Science and Pollution Research	6	9	-	85	13	5.190
Atmospheric Pollution Research	5	9	2.5	86	10	4.831
Environment Development and Sustainability	5	7	-	155	7	4.080
Environmental Research Letters	5	7	2.5	62	8	6.947
International Journal of Environmental Research and Public Health	5	7	1.667	55	14	4.614
Journal of Cleaner Production	5	5	2.5	78	5	11.072
Journal of Environmental Sciences	5	9	2.5	119	9	3.120
Scientific Reports	5	6	1.667	101	6	4.996
Sustainable Cities and Society	5	6	1.667	204	6	10.696
Urban Climate	5	9	1.667	82	9	6.663
Environmental Science & Technology Letters	4	6	1.333	141	6	11.558

NP, number of publications; *IF*, impact factor; *TC*, total citation

indicate that genuine air quality improvements were notably more limited than some earlier reports or observational data suggested. Sulaymon et al. (2021) published in *Atmospheric Research* on “COVID-19 pandemic in Wuhan: ambient air quality and the relationships between criteria air pollutants and meteorological variables before, during, and after lockdown.” They discovered that although the COVID-19 pandemic had numerous adverse effects on human health and the global economy, the reductions in air pollution and significant improvement in ambient air quality likely had substantial short-term health benefits. This study improves the understanding of the mechanisms that lead to air pollution under diverse meteorological conditions and suggest effective ways of reducing air pollution in Wuhan. Bar et al. (2021) also collaborated to publish “Impacts of partial to complete COVID-19 lockdown on NO₂ and PM_{2.5} levels in major urban cities of Europe and US” in *Cities*.” In the study, the researchers outlined that improvement in air quality during COVID-19 may be temporary. Still, regulatory bodies should learn to reduce air pollution long-term concerning the trade-offs between the environment, society, and economic growth. Policymakers should address the intersection of urban design, health, and the environment to protect public health. Sustainable urban policies could be adopted to build urban resilience against future emergencies.

The researchers further utilized highly impactful articles to comprehend the implication of a particular area of interest. The highly impactful articles compute a high document level in a specific subject. Table 6 reflects the highly impactful articles based on total citations related to the COVID-19 social lockdown and its impact on air pollution. The most highly impactful work was “COVID-19 lockdowns cause global air pollution declines,” published by Venter et al. (2020) in *Earth, Atmospheric, and Planetary Sciences*, with 340 citations which accounts for 12.9% of the top fifteen most cited publications. However, all the highly cited documents were published in 2000 and were cited from *Science of the Total Environment*. This article expounded on the topic under discussion and found empirical evidence for a link between global vehicle transportation declines and the reduction of ambient NO₂ exposure. The researchers concluded that, while the state of global lockdown is not sustainable, there is a potential for mitigating public health risks by reducing “business as usual” air pollutant emissions from economic activities. The second most cited document by Sicard et al. (2020) takes another dimension. This study highlights the challenge of reducing the formation of secondary pollutants such as O₃, even with strict measures to control primary pollutant emissions. The study revealed that the lockdown effect on O₃ production was 10% higher than the weekend effect in Southern Europe and 38% higher in Wuhan, while

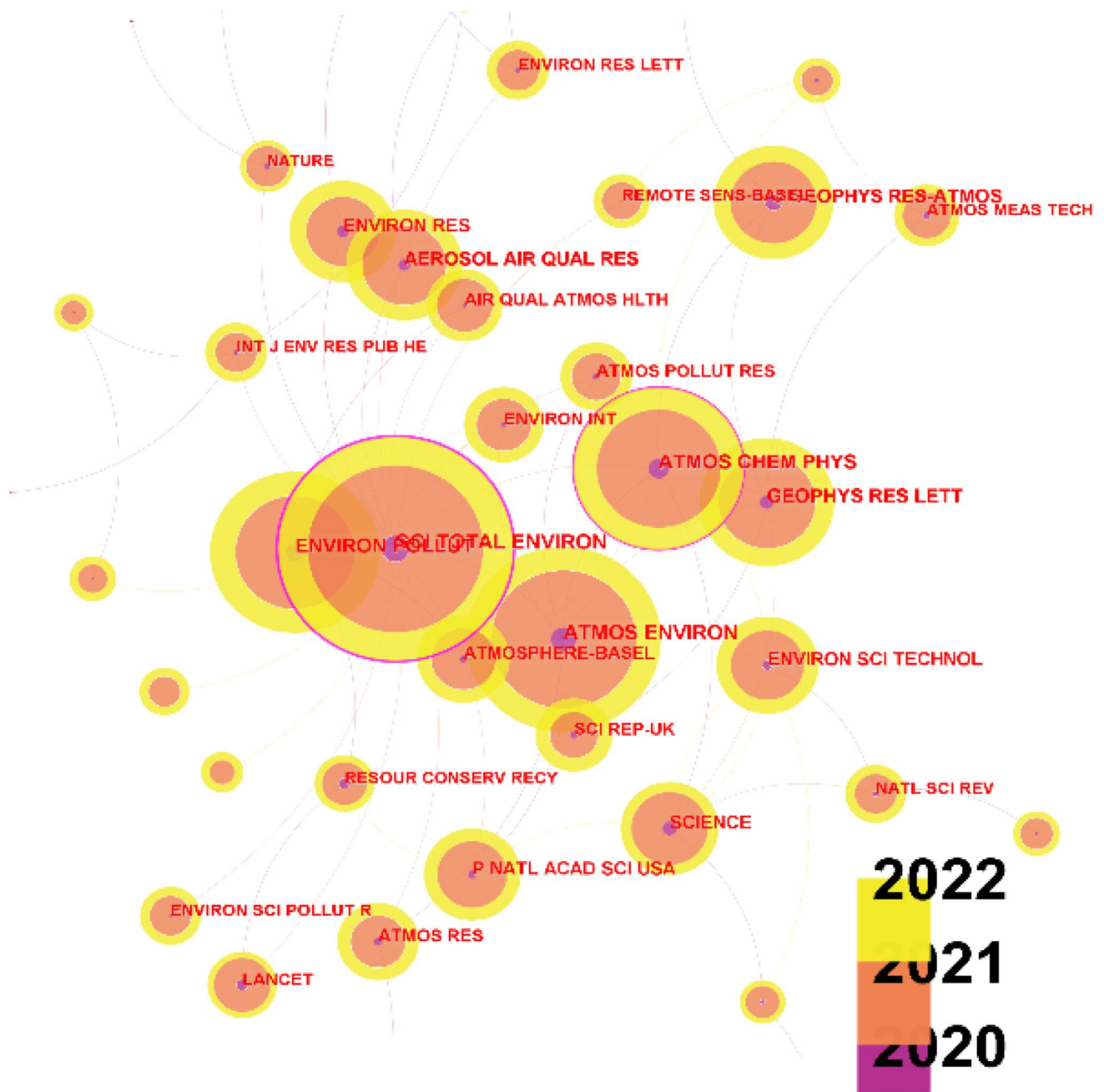


Fig. 5 Co-citation network of the most productive journals. Note: purple rings represent the degree of centrality; node size depicts the frequency of co-citations

for PM, the lockdown had the same effect as weekends in Southern Europe.

Keyword analysis: current and future perspectives

Keyword analysis and research hotspot

By analyzing the frequency of keyword occurrence, a researcher may find beneficial information such as a

document’s objectives, methods, and perspectives (Afrane et al. 2022a, b; Agyepong and Liang 2022; Effah et al. 2022; Jin et al. 2022). The author keyword is the list of keywords in the article and is a useful part of data for the scientific community on research-changing aspects and evaluations (Chen 2006; Zhang et al. 2020a). The keyword plus on the other hand is created from the titles of the cited documents and denotes an expanded scope of the search to capture relevant and related terms (Afrane et al. 2022a, b; Zhang and

Table 5 Top 10 performing authors

Authors	Number of publications	Total citation	h-index
Wang Y.	11	152	6
Li L.	8	354	5
Wang H.L.	8	144	5
Kumar S.	7	143	5
Liao H.	7	121	3
Liu C.	7	29	3
Zhang J.	7	104	5
Zhao T.L.	7	94	4
Fu Q.Y.	6	351	3
Hu J.L.	6	63	2

Liang 2020). Keywords and keyword plus analyses suggest a practical method to find new research prospects on a specific theme (Afrane et al. 2022a, b; Khan et al. 2021; Zhang et al. 2020b). The researchers adopted CiteSpace to map the keyword co-occurrence network to comprehend the progress of research interests and find hotspots in this field. So, the co-occurrence and frequency analysis of keywords and keyword plus may help determine hot topics and boundaries in a research field (Chen et al. 2016; Huang et al. 2020).

The data gathered, as shown in Table 6, displays that the most frequently occurring author keywords were “Covid-19” (238), “Air-quality” (126), “Lockdown” (111), “Air-pollution” (89), “Covid-19 lockdown” (63), “PM_{2.5}” (53), “NO₂” (42), “Particulate Matter” (31), “Ozone” (27), and “PM₁₀” (23), involving the implication of evaluating the impact of COVID-19 on the air pollution topic. In descending order, keywords with the highest centrality in the network were improved air quality, pollution, impact, emissions, and Covid-19 lockdowns (Fig. 7). Similarly, the keyword plus network showed that the most frequent words were “Pollution” (122), “Impact” (105), “Air-quality” (90), “PM_{2.5}” (84), “Ozone” (68), “Quality” (60), “Emissions” (58), and “Particulate Matter” (51) (Table 7).

Figure 7 shows the co-occurrence network of keywords that appeared more than ten times. The size of the circle is proportional to the keyword frequency, while the lines connecting the nodes show the relationship between keywords. The network comprised 107 nodes and 361 links with a density of 0.06. The tight structure of the network indicates that the keywords are closely interlinked.

The main research direction of the impact of COVID-19 social lockdowns is highlighted in Fig. 8 according to the frequently occurring author keywords and keyword plus. It can be concluded that research focus using both author keyword and keyword plus have fairly been the same inferring from the figure. In no systematic order, for author keyword analysis, COVID-19, air quality, air pollution, and

lockdown and for keyword plus pollution, air quality, impact, and PM_{2.5} have been the top 4 across all research studies. It is worth mentioning that there were not many differences in the research trends of the overall author keyword and keyword plus results. The basic difference is that some of the author’s keywords, like COVID-19 and SARS-COV-2, were not prominent in the keyword plus domain. Moreso, Fig. 8 showed that PM₁₀ generally was not prominent in the study in both author keyword and keyword plus in the top 50 author keywords and keyword plus.

The section is concluded with the main research direction of the most productive countries/regions and journals. In Fig. 9, a three-field plot is created with the top 10 countries on the left, the top 10 journals on the right, and the top 10 keywords in the middle. Based on the figure, it can be realized that the top 5 keywords from these ten nations are the same as the global, as shown in Fig. 6. This validates the notion that the research direction is frequently determined by these ten nations, especially China, India, and the USA. The top 10 journals had contributed to publication employing the top ten keywords as seen in the figure.

The development of broad and main themes is captured using a thematic evolution mapping, as displayed in Fig. 10. This figure shows the influence of COVID-19 social lockdowns on urban air quality throughout the novel virus’s propagation from 2020 to 2022 and how the research trend will continue into 2023 and beyond. The year 2021 was the timeline’s cutting point, given the study’s coverage. The network of lines connecting one theme to another illustrates how a theme’s research emphasis has developed with time. The bigger the size of the network, the more significant the themes’ influence in that period is.

The research started with ten major themes: meteorology, COVID-19 lockdown, traffic, aerosol, COVID-19, aerosol optical depth (AOD), particulate matter, NO₂, sentinel 5-p, emission, and remote sensing. Some themes, such as COVID-19, remained constant in the top 5 since the starting period and accounted for the largest theme. COVID-19 can, thus, be described as a core study area in this research field. Furthermore, themes such as NO₂ and particulate matter were essential themes during the initial stages of the coronavirus outbreak (2000–2021) but declined within 2020–2023. However, the attention on the AOD has been revitalized in recent years and, thus, a major theme in 2022–2023 (AOD), coupled with research on the COVID-19 pandemic.

Current and future perspectives

Recent air pollution research highlights that half of the annual premature deaths in China, India, and the USA result from indoor air pollution (Dedoussi et al. 2020; Jyoti 2020; Tohno and Chatani 2021). Subsequently, the recent COVID-19 social

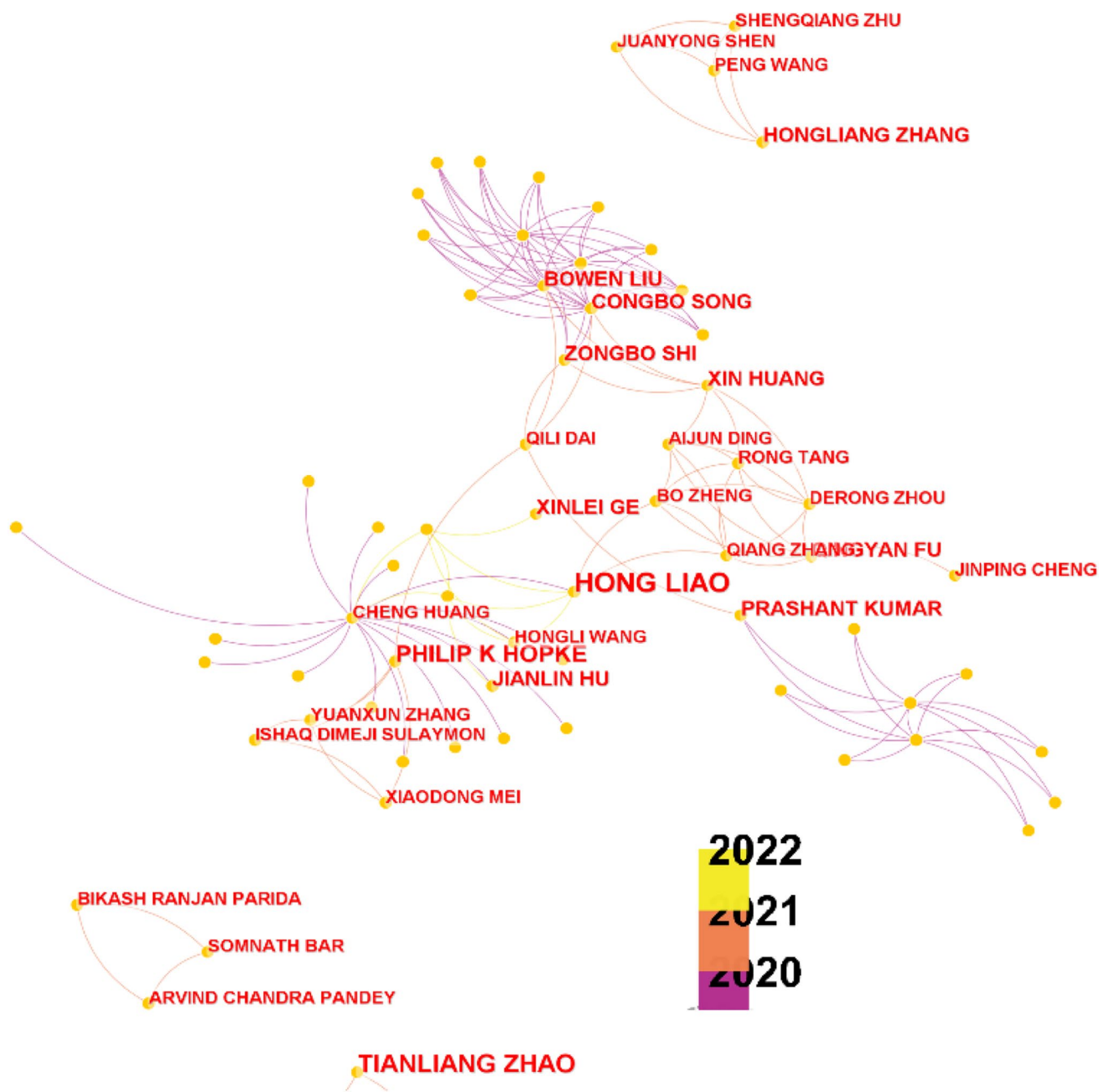


Fig. 6 Academic collaboration among the top 10 most productive authors

lockdown has proven that we can improve and achieve better air quality and a clean environment (Arora et al. 2020; Venter et al. 2020). The WHO estimates that about 4.2 million people die from ambient air pollution yearly. They further project that air pollution is also associated with 26% of deaths caused by respiratory disorders, 25% of deaths from chronic obstructive pulmonary disease (COPD), and 17% of deaths from heart attacks and strokes (Isaifan 2020; Khan et al. 2021). The findings from the keyword analysis in Figs. 7, 8, and 9 show that much of the current research has focused on the impacts of

COVID-19 lockdowns on air quality, highlighting how pollution and emission levels reduced during those lockdowns periods and how the identified pollutants have significant impacts on air quality and public health.

For instance, Terpi and Czwojdzki (2021) concluded that PM_{10} was associated with COVID-19 incidence and mortality in different provinces only in certain months. Namdar-khojasteh et al. (2022) analyzed the relationships between COVID-19 cases and both short-term (6 months) and long-term (60 months) exposures to eight air pollutants (NO,

Table 6 Highly impactful articles based on total citations during 2020–2022

Articles	Journal	Total citations	Reference
COVID-19 lockdowns cause global air pollution declines	Earth, Atmospheric, and Planetary Sciences	340	Venter et al. 2020
Amplified ozone pollution in cities during the COVID-19 lockdown	Science of the Total Environment	334	Sicard et al. 2020
Enhanced secondary pollution offset reduction of primary emissions during COVID-19 lockdown in China	National Science Review	332	Qi et al. 2020
The short-term impacts of COVID-19 lockdown on urban air pollution in China	Nature Sustainability	288	He et al. 2020
Air quality changes during the COVID-19 lockdown over the Yangtze River Delta Region: an insight into the impact of human activity pattern changes on air pollution variation	Science of The Total Environment	270	Li et al. 2020
Assessing air quality changes in large cities during COVID-19 lockdowns: the impacts of traffic-free urban conditions in Almaty, Kazakhstan	Science of The Total Environment	217	Kerimray et al. 2020
COVID-19 lockdown effects on air quality by NO ₂ in the cities of Barcelona and Madrid (Spain)	Science of The Total Environment	195	Baldasano, 2020
Temporary reduction in fine particulate matter due to “anthropogenic emissions switch-off” during COVID-19 lockdown in Indian cities	Sustainable Cities and Society	126	Kumar et al. 2020
Response of major air pollutants to COVID-19 lockdowns in China	Science of The Total Environment	101	Pei et al. 2020
Disentangling the Impact of the COVID-19 lockdowns on urban NO ₂ from natural variability	Geophysical Research Letters	101	Goldberg et al. 2020
Short-term and long-term health impacts of air pollution reductions from COVID-19 lockdowns in China and Europe: a modelling study	The Lancet Planetary Health	95	Giani et al. 2020
The COVID-19 lockdowns: a window into the earth system	Perspectives	90	Diffenbaugh et al. 2020
Nonuniform impacts of COVID-19 lockdown on air quality over the USA	Science of The Total Environment	84	Chen et al. 2020
Impact of COVID-19 lockdown on NO ₂ , O ₃ , PM _{2.5} , and PM ₁₀ concentrations and assessing air quality changes in Baghdad, Iraq	Science of The Total Environment	82	Hashim et al. 2021
Abrupt but smaller than expected changes in surface air quality attributable to COVID-19 lockdowns	Science Advances	81	Shi et al. 2021

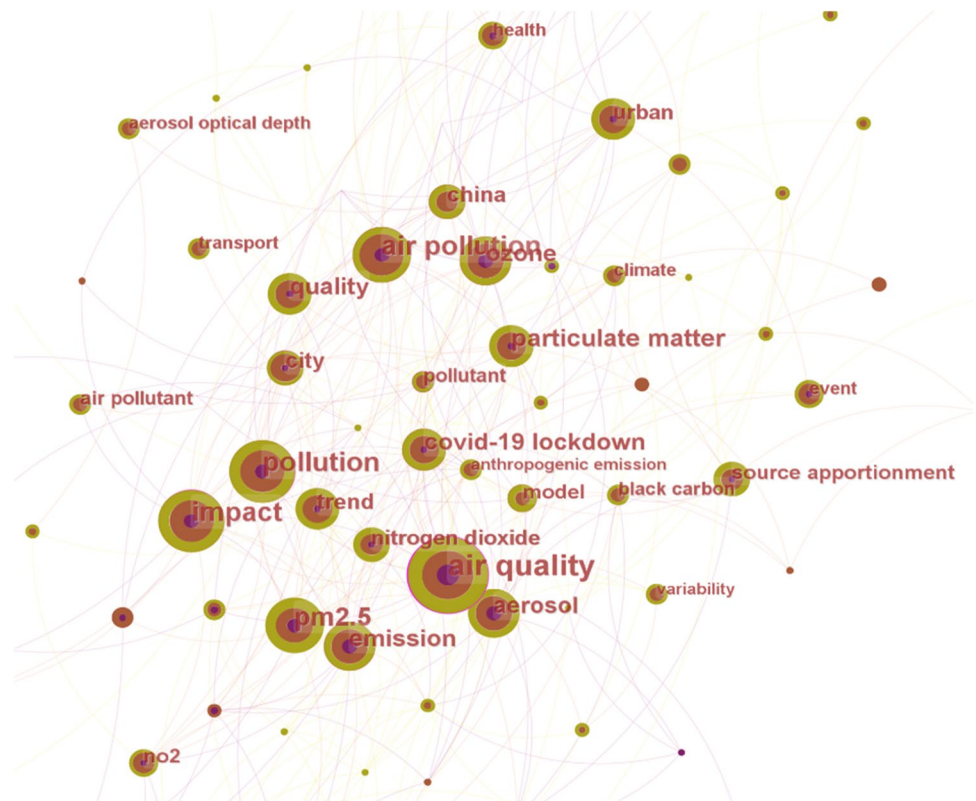
NO₂, NO_x, CO, SO₂, O₃, PM_{2.5}, and PM₁₀) in Tehran city, Iran. They found that exposure to air pollutants can increase the number of infected people by transmitting the virus through the air or predisposing people to the disease over time. Also, Travaglio et al. (2021) explored potential links between major fossil fuel-related air pollutants and SARS-CoV-2 mortality in England. They compared current SARS-CoV-2 cases and deaths from public databases to regional and subregional air pollution data monitored at multiple sites across England. They found that a small increase in air pollution leads to a large increase in England’s COVID-19 infectivity and mortality rate.

Chattopadhyay and Shaw (2021) also empirically explored the relationship between exposure to air pollutants, that is, sulfur dioxide, nitrogen dioxide, and particulate matter (SO₂, NO₂, and PM₁₀) and COVID-19 infection at the smallest administrative level (ward) of Mumbai City in

India. They concluded that if explicit pollutants and other factors play a considerable role in COVID-19 infection, it has strong implications for any mitigation strategy development to curtail the spreading of the respiratory disease. The findings of the highlighted studies suggest that in a particular geographical area with high air pollution, there is a likelihood of a higher outbreak and spread of the COVID-19 pandemic compared to areas with less air pollution. Hence, air pollution must drop during the COVID-19 pandemic to save human lives.

COVID-19, to many, looked unending, but the quick countermeasure, especially the social lockdown adopted by various governments across the globe, has been very effective in solving many environmental issues that were costly to fight. Although the COVID-19 social lockdowns were adopted as a temporal countermeasure, they have positively impacted the environment, significantly improving air

Fig. 7 Author keyword co-occurrence



quality in various geographical locations. The most vulnerable people to COVID-19 are those living in poor air quality geographical areas, especially with high PM concentrations (Domingo et al. 2020). However, due to the emergence of COVID-19 and the quick adoption of the COVID-19 social lockdowns, various countries are in a better position to develop a cleaner future for upcoming generations.

For instance, Briz-redón et al. (2021) investigated the impact of a short-term lockdown from March 15 to April 12, 2020, on the atmospheric levels of CO, SO₂, PM₁₀, O₃, and NO₂ over 11 representative Spanish cities. The results show that the 4-week lockdown significantly reduced the atmospheric levels of NO₂ in all cities, except for the small

city of Santander, and CO, SO₂, and PM₁₀ in some cities, but resulted in an increase of O₃ level. Wang et al. (2021) exploited the impact of pandemic-induced human mobility restrictions on urban air quality across China in response to the COVID-19 pandemic. Their findings shed new light on the role of a policy intervention in pollution emissions while also providing a roadmap for future research on the pollution effect of the COVID-19 pandemic. Seo et al. (2020) also contributed to this ongoing discussion in Korea by comparing the air quality between 2020 and the previous 3 years, focusing on the two cities (Seoul and Daegu) where coronavirus is spreading faster. In both cities, they found a significant decrease in PM_{2.5}, PM₁₀, CO, and NO₂. Consequently, the effects of social lockdowns have maximized improvements in air quality due to reduced transboundary pollutants.

Figures 8 and 10 also illustrate the future perspectives of research in this area, with future combat strategies have been displayed in Fig. 11. Results suggest that future studies may still consider how for example, the remote sensing capabilities of Tropomi can aid in improving air quality by providing valuable information about atmospheric pollutants so policy and mitigation efforts can be implanted to reduce pollution and protect human health. Others can also examine the use of Sentinel-5p data to map the ambient PM_{2.5} and examine changes in AOD during the COVID-19 lockdown period, even across areas in a particular country or across countries so that valuable information will help understand

Table 7 Author keyword and author keyword plus networks

Author keywords	Total counts	Keyword plus	Total counts
Covid-19	238	Pollution	122
Air-quality	126	Impact	105
Lockdown	111	Air-quality	90
Air-pollution	89	PM _{2.5}	84
Covid-19 lockdown	63	Ozone	68
PM _{2.5}	53	Quality	60
NO ₂	42	Emissions	58
Particulate Matter	31	Particulate Matter	51
Ozone	27	China	46
PM ₁₀	23	Trends	46

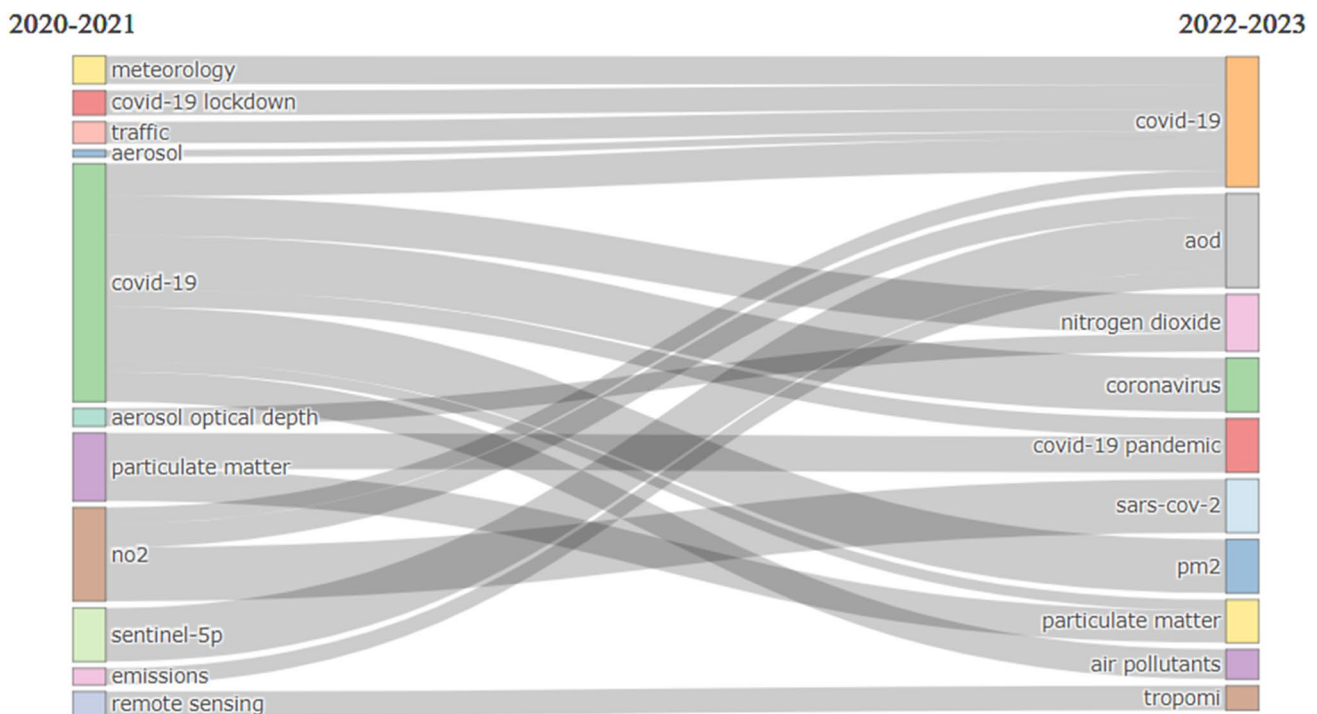


Fig. 10 Thematic evolution of the impact of COVID-19 social lockdown on air-quality

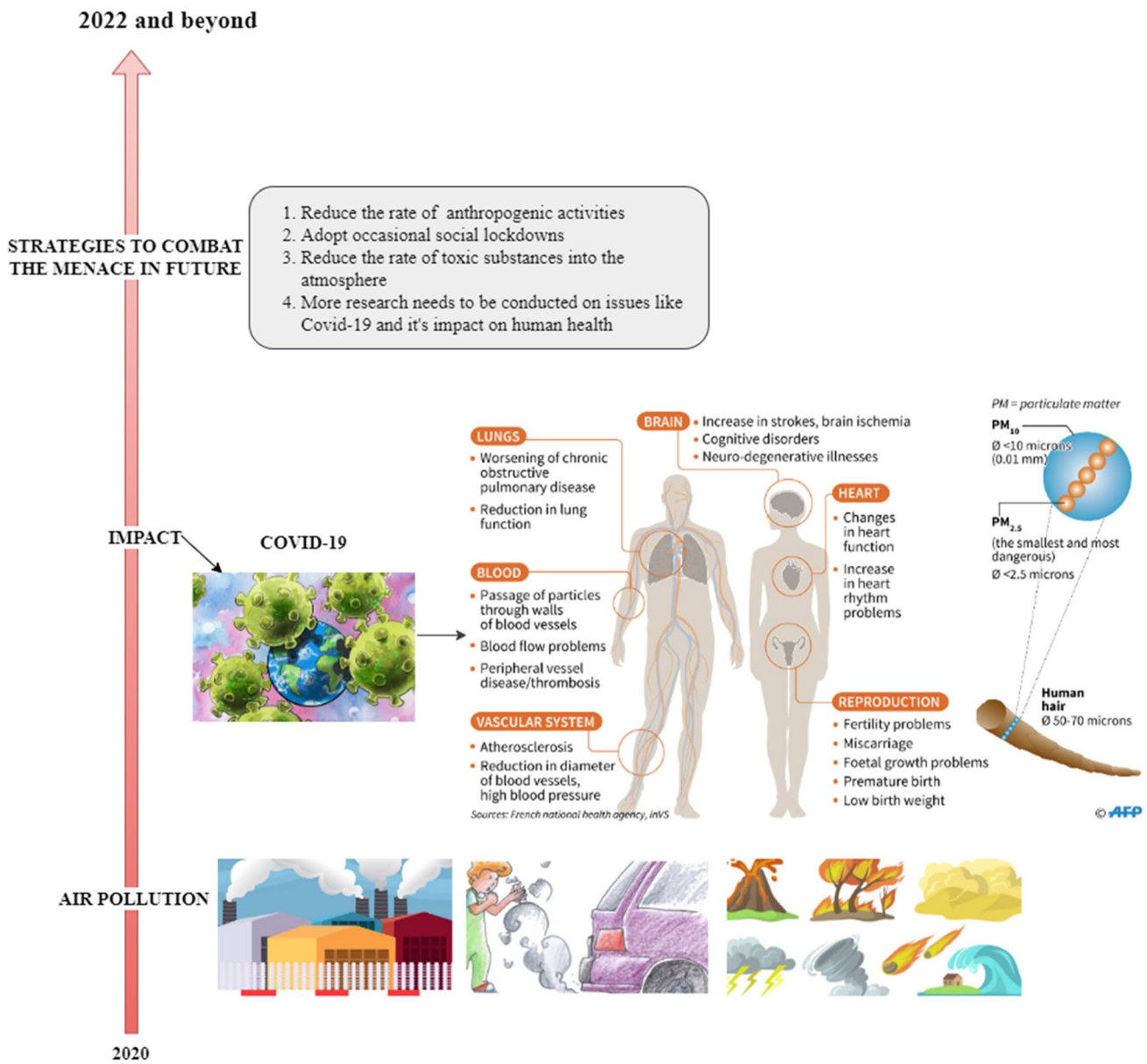
explore the measure of this auxiliary effect of air pollution on the COVID-19 pandemic. Also, on a fast-paced show, conclusions from other studies have shown that inhabitants of highly polluted cities risk being infected with COVID-19, showing most symptoms after the quick spread. COVID-19 and air pollution are interconnected to population density and spatial issues. By implication, there is a need for more distinct research to explore the advancements of the COVID-19 issues in a differentiated group across various continents.

The COVID-19 pandemic and air pollution go hand in hand, and the lockdown procedures have been relaxed in most countries. Both air pollution and COVID-19 have perhaps unsettled the disadvantaged populaces more severely due to higher exposure rates. As a result, actions to lower the adverse effect of both COVID-19 and air pollution should be concentrated on disadvantaged groups in particular, where the need is critical (Aboagye et al. 2022; Banks et al. 2020; United Nations 2020). Fundamentally, we cannot associate a bright side to the novel COVID-19 pandemic due to the several losses of lives; nevertheless, these research discussions suggest the provision of health benefits from air pollution reductions by reducing human mobility and industrial activities. Hence, there is a fortune amidst this misfortune (Aboagye et al. 2021).

Implications of this study

Several implications can be drawn from this review article for analyzing the scientific productivity of the effect of COVID-19 on air pollution. This discussion provided data and significant information to help future researchers, policymakers, government officials, and other stakeholders understand and appreciate the roles of countries, authors, and specific research themes of air pollution or air quality inferred from COVID-19 social lockdowns on environmental sustainability. Thus, this research explained the influence of each country's research productivity and prominent authors associated with COVID-19 social lockdowns and air pollution research at a global level.

The literature presents extensive evidence on existing themes and points of view for further research by identifying highly impactful research hotspots. For example, the assessment and discussions on the scientific country productivity indicate the research significance of a specific country in the future. Equally, a highly impactful article implies the importance of the research for a particular topic of interest which can be discussed with other bibliometric considerations, such as relationships and the number of citations. Due to new COVID-19 waves or variants worldwide, environmental researchers should investigate these concerns, especially using a bibliometric approach, to gain a deep understanding of present and future studies.



Source: Authors construct

Fig. 11 Impact of air pollution on the COVID-19 pandemic and future combat strategies

Conclusion and limitations

This current study analyzed data gathered from the Web of Science Core Collection with the help of quantitative and qualitative research tools to map the characteristics of research output on the impact of COVID-19 social lockdowns on air quality from 2020 to 2022. Several bibliometric evaluations were studied regarding the countries' scientific productivity, keywords analysis, and dominant authors. Most of the articles were issued in journals like Atmosphere (38, 7.54%), Science of the Total Environment (37, 7.31%),

and Aerosol and Air Quality Research (32, 6.35%). Regarding the qualitative part, Venter et al.'s (2020) contributions were the most cited research in Earth, Atmospheric, and Planetary Sciences, totaling 340 citations. This review paper carefully examined the present significance of the effect of air pollution in what looks like an unending COVID-19 pandemic and social lockdown and future perceptions. Thus, this research gives experts data, proof, and knowledge of how COVID-19 social lockdowns affect air pollution, especially in metropolitan locations.

Amidst these contributions, the study is limited in the following ways. Over the years, there has been an underlying problem with bibliometric methods. This approach usually centers on the research outputs rather than content; however, the researchers were able to capture contents as part of the discussions for this study. Additionally, selection bias is possible since the study documents were fundamentally based on the Web of Science Core Collection. Although the Web of Science is broad and reliable, more sources like Scopus and Google Scholar could present a more thorough concept and ideas. Nevertheless, if these limitations are solved, we do not expect a substantial difference from the findings of the current review.

Abbreviations AIDS: acquired immune deficiency syndrome; B.P: blood pressure; COPD: chronic obstructive pulmonary disease; EPA: Environmental Protection Agency; HIV: human immune virus; ICU: intensive care unit; IF: impact factor; MCP: multiple country publications; PM: particulate matter; SARS: severe acute respiratory syndrome; SCP: single country publication; WHO: World Health Organization; WoS: Web of Science

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Data availability Not applicable

Declarations

Ethics approval Not applicable

Consent to participate All authors agreed to contribute to this study.

Consent for publication All authors agreed.

Competing interests The authors declare no competing interests.

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