Environmental Sustainability (2022) 5:5–23
https://doi.org/10.1007/s42398-021-00213-6

REVIEW

The impact of the COVID-19 lockdown on global air quality: A review

Lala Saha[1] · Amit Kumar[2] · Sanjeev Kumar[1] · John Korstad[3] · Sudhakar Srivastava[4] · Kuldeep Bauddh[1]

Received: 21 August 2020 / Revised: 8 November 2021 / Accepted: 26 December 2021 / Published online: 7 February 2022

Abstract

The coronavirus disease 2019 (COVID-19) was declared a pandemic by the World Health Organization (WHO) on March 11, 2020. As a preventive measure, the majority of countries adopted partial or complete lockdown to fight the novel coronavirus. The lockdown was considered the most effective tool to break the spread of the coronavirus infection worldwide. Although lockdown damaged national economies, it has given a new dimension and opportunity to reduce environmental contamination, especially air pollution. In this study, we reviewed, analyzed and discussed the available recent literature and highlighted the impact of lockdown on the level of prominent air pollutants and consequent effects on air quality. The levels of air contaminants like nitrogen dioxide (NO_2), sulphur dioxide (SO_2), carbon monoxide (CO), and particulate matter (PM) decreased globally compared to levels in the past few decades. In many megacities of the world, the concentration of PM and NO_2 declined by > 60% during the lockdown period. The air quality index (AQI) also improved substantially throughout the world during the lockdown. Overall, the air quality of many urban areas improved slightly to significantly during the lockdown period. It has been observed that COVID-19 transmission and mortality rate also decreased in correlation to reduced pollution level in many cities.

Keywords COVID-19 · Lockdown · Global air pollution · Greenhouse gases · Particulate matter

Introduction

Coronavirus disease (COVID-19) is an ongoing devastating pandemic. As of November 05, 2021, there were more than 248,467,363 cases of coronavirus-infected persons and 5,027,183 deaths worldwide as shown in Fig. 1 (WHO 2021). COVID-19 originated from Wuhan, the capital city of Hubei Province in the People's Republic of China, in the month of December 2019 (Huang et al. 2020). Due to its highly contagious nature, it spread around the world very quickly. The Centers for Disease Control and Prevention (CDC) reported that on June 17, 2020, 216 countries and territories had confirmed COVID-19 cases (CDC 2020).

To break the chain and minimize the spread of the coronavirus, majority of the nations implemented a complete lockdown (Long 2020). As a result, most industrial activities were halted and public and personal transport was restricted during the lockdown period. As of February 18, 2021, many countries like Australia, Belgium, India, France and Spain have initiated fresh partial lockdowns and implemented new guidelines for highly populated areas. These measures have caused a massive impact on the socio-economic conditions of all nations worldwide. On the other hand, positive impacts of stringent lockdown were seen on environmental pollution, especially on water quality (Mandal and Pal 2020; Yunus et al. 2020) and air quality (Gautam 2020a, b; Saadat et al. 2020; Srivastava et al. 2020; Ankit et al. 2021). Air pollution is known to cause mass-scale health problems, particularly in densely populated developing nations (WHO 2006). The long term exposure to air contaminants including $PM_{2.5}$ and ozone (O_3) causes ~ 8.8 million excess deaths yearly, while NO_2 is responsible for 4 million new pediatric asthma cases every year (Burnett et al. 2018; Achakulwisut

✉ Kuldeep Bauddh
kuldeep.bauddh@cuj.ac.in

[1] Department of Environmental Sciences, Central University of Jharkhand, Ranchi 835205, India

[2] Department of Botany, Lucknow University, Lucknow 226007, India

[3] Department of Biology and Global Environmental Sustainability, Oral Roberts University, Tulsa, OK 74171, USA

[4] Plant Stress Biology Laboratory, Institute of Environment and Sustainable Development, Banaras Hindu University, Varanasi 221005, India

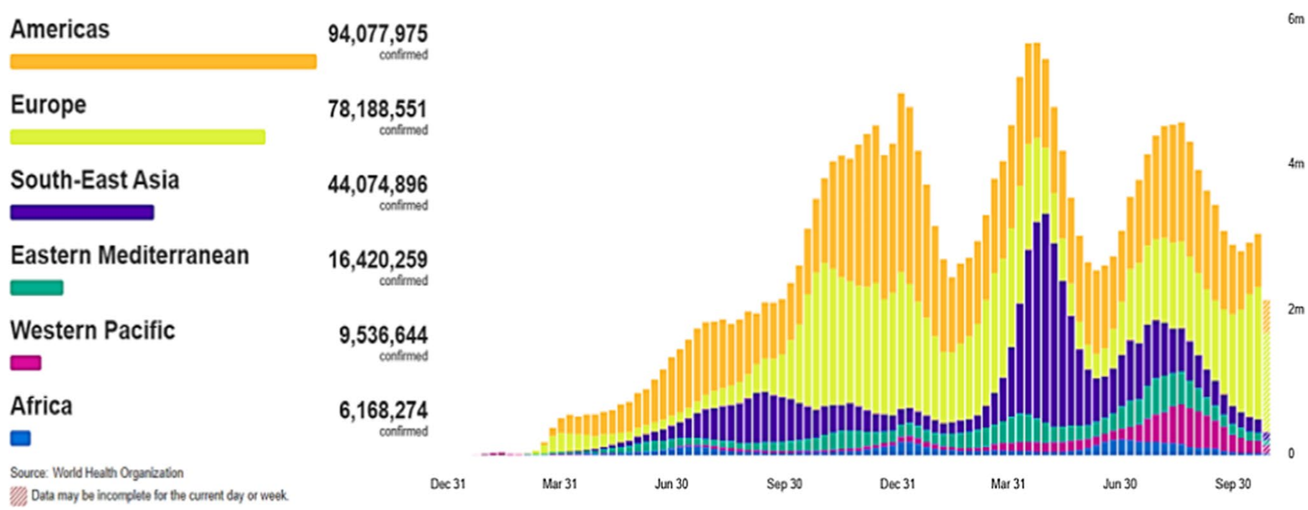

Fig. 1 Total confirmed cases throughout the world on November 05, 2021 (Source-WHO 2021)

et al. 2019; Lelieveld et al. 2020). Due to lockdown measures, the reduction in air contaminants and improvement in AQI were seen in several countries like India and China (Bao and Zhang 2020; Mahato et al. 2020; Srivastava et al. 2020). The proportion of reduction in air pollutants presumably depended on the stringency of lockdown. Apart from this, many recent studies have found a positive relationship between the increase in air pollution with COVID-19 infection and mortality rates (Coccia 2020; Sarmadi et al. 2020; Shakoor et al. 2020; Wu et al. 2020; Kumar 2020; Son et al. 2020; Copat et al. 2020; Marquès and Domingo 2021). It is necessary to understand trends in the reduction of air contaminants in different countries in order to help policymakers plan and implement future strategies to combat air pollution along with handling measures for COVID-19 and similar pandemic situations. The main objective of this review is to assess the worldwide impact of the COVID-19 lockdown on air quality, particularly on the level of $PM_{2.5}$, PM_{10}, NO_2, CO and SO_2. The impact of the COVID-19 pandemic lockdown (CPL) on air quality was assessed in the United States of America (USA), China, India, Brazil, Italy, Spain, France, Norway, Germany, Netherland, Switzerland, Kazakhstan, Mongolia, Morocco, Iran, Peru, Australia, Malaysia, United Arab Emirates (UAE), Austria, Portugal and the Czech Republic.

Pollution assessment during COVID-19

During the current COVID-19 pandemic (CP), human activities, which are considered as major sources of various pollutants, were stopped partially to completely almost globally, resulting in reduced pollution levels (Zambrano-Monserrate et al. 2020; Muhammad et al. 2020; Saadat et al. 2020; Gautam 2020b). Community mobility reports (https://www.google.com/covid19/mobility/) depict that human mobility decreased by 90% between 23 February 2020 to 05 April 2020, specifically in European countries (Muhammad et al. 2020). During the same time, a sharp decline in air pollution was noticed worldwide. Climatologists predicted that greenhouse gases (GHGs) such as carbon dioxide (CO_2), methane (CH_4), and nitrous oxide (NO) emissions declined to levels not observed since World War II (Global Carbon Project 2020; Zambrano-Monserrate et al. 2020). Some recent studies have shown that atmospheric emission of multiple pollutants such as NO_2, CO_2, CO, SO_2, PM_{10}, and $PM_{2.5}$ significantly decreased (ESA 2020; Saadat et al. 2020; Dantas et al. 2020; Mahato et al. 2020; Quéré et al. 2020; Ju et al. 2021; Mostafa et al. 2021). Scientists from the National Aeronautics and Space Administration (NASA) revealed the reduction in NO_2 pollution near Wuhan and the trend continued across China (NASA 2020; Dutheil et al. 2020).

Studies in different cities, residential areas, commercial areas, tourist spots, industrial areas, mining sites, highways, and roads have been assessed for pollution levels in various parts of the world (Chakraborty and Maity 2020; Mahato et al. 2020; Kotnala et al. 2020; Dantas et al. 2020; Nakada and Urban 2020; Sicard et al. 2020). Zambrano-Monserrate et al. (2020) predicted both indirect positive and negative effects of the current pandemic situation on different environmental components. They concluded that air quality and noise levels improved along with cleaner seashores. However, waste generation increased due to adoption of measures for health safety while recycling and management of waste reduced due to imposition of lockdown which lead to the contamination of water and soil (Zambrano-Monserrate et al. 2020). Another study assessed the data of the

European Space Agency (ESA) and NASA and concluded that the pollution level in Wuhan (China), Spain, Italy, and the USA declined by 30% during the current lockdown period (Muhammad et al. 2020). Environmental impacts of COVID-19 became visible in Venice, Italy, where the water canals looked clearer than normal, which may be due to the absence of sediment resuspension compared to the past (Braga et al. 2020). The effects of motorboats on mixing of sediments and pollutants decreased, resulting in clearer water and fish could be seen again in the canals (Saadat et al. 2020). A decrease in the number of tourists in the city also led to a decrease in water pollutants. The study also reported that due to the lockdown measures, the land surface temperature (LST) was reduced by 2.74 to 7.06 °C from the pre-lockdown LST range of 31.25 to 35.11 °C and the noise level dropped to < 65 dBA from > 85 dBA after 18 days of lockdown (Mandal and Pal 2020). The same study reported that the water quality of an adjacent river improved in terms of pH, total dissolved solids (TDS), and dissolved oxygen (DO) after 30 days of lockdown. Yunus et al. (2020) also analyzed the remote sensing images of pre and post-lockdown and projected that the surface water quality of Vembanad Lake in India improved during the lockdown in terms of suspended particulate matter (SPM), which decreased by 15.9% compared to pre-lockdown periods. Other studies from different countries also reported reduction in level of environmental contaminants, especially gaseous pollutants, which are summarized in Tables 1, 2, 3, 4, 5, 6, 7 and 8.

Worldwide reduction in major air contaminants

India

India has taken various preventive measures to combat the CP. However, there were over 34,333,754 confirmed COVID-19 cases, with 459,873 human deaths as of November 05, 2021 (5:11 pm CET, 05 November 2021) (WHO 2021). The Indian government implemented the first phase lockdown 1.0 for three weeks starting 24 March to 14 April and then extended it for three consecutive lockdowns until 31 May 2020. Then, the unlock phase started from 1–30 June as unlock1.0 with some relaxation that continued in unlock 2.0 (1–31 July), unlock 3.0 (1–3 August) with increasing relaxations including allowed inter and intra-state transportation, unlock 4.0 (1–30 September), unlock 5.0 (1–31 October), and unlock 6.0 (1–30 November) with partial reopening of schools. The continuous nationwide lockdown impacted the economy negatively and the environment positively. The pollution level in many Indian cities improved during the first to the fourth phase of lockdown compared to pre-lockdown periods of 2020 and the same months of the previous year (Mahato et al. 2020; Sharma et al. 2020; Singh and Chauhan 2020; Kumar et al. 2020; Srivastava et al. 2020; Jain and Sharma 2020; Kumar 2020). During the lockdown period, the air quality of Delhi, India's capital, improved significantly (Mahato et al. 2020; Srivastava et al. 2020; CPCB 2020). Mahato et al. (2020) recorded that the level of pollutants such as NO_2 and CO decreased by 52.68% and 30.35% respectively, during the lockdown period. The concentration of PM_{10} and $PM_{2.5}$ decreased > 50% in the pandemic period compared to the pre-lockdown phase. When compared to the same period of the previous year, PM_{10} and $PM_{2.5}$ levels declined by 60 and 39% respectively, in the city. In the year 2020, the air quality of the industrial and major transport areas of Delhi improved by 60% (Table 1) (Mahato et al. 2020). In Delhi's busy commercial area (ITO), the concentration of $PM_{2.5}$ was 124.5 μg m^{-3} before lockdown and declined to 46 μg m^{-3} during the lockdown period (Kotnala et al. 2020). Srivastava et al. (2020) studied the impact of the entire lockdown in two major cities of India; New Delhi and Lucknow. They found that there was a significant decline in the level of $PM_{2.5}$ from 85 to 456 μg m^{-3} (before lockdown) to 47–204 μg m^{-3} (after lockdown). The concentrations of NO_2 in Lucknow before and after the lockdown were 22–158 μg m^{-3} and 3–59 μg m^{-3}, respectively. The concentration of CO decreased from 15–150 μg m^{-3} to 5–98 μg m^{-3} in New Delhi and 20–199 μg m^{-3} to 3–55 μg m^{-3} in Lucknow.

Sharma et al. (2020) investigated the impact of lockdown on 22 cities of North, South, West, East and Central regions of India and showed that AQI decreased by 44, 33, 32, 29 and 15% respectively, compared to the same period of previous year. The overall particulate matter declined by 52% throughout the nation due to restrictions in the lockdown period. However, the concentration of O_3 increased by 17% compared to 2019 and was 10% higher compared to the last three year average. Another study found similar results from the riverside mining areas of eastern India, where the PM_{10} concentration was 189–278 μg m^{-3} before lockdown and 50–60 μg m^{-3} after 18 days of lockdown (Mandal and Pal 2020). That clearly showed that a significant portion of particulate matter attenuated during the lockdown period. Satellite data collected from Sentinel–5P on aerosol optical depth (AOD) variations indicated that the levels of aerosol/air pollution over the northern part of India recorded lowest levels in 20 years for the same period of time of the year 2020 (Gautam 2020a). Kumar et al. (2020) analyzed the concentration of $PM_{2.5}$ up to fourth phase lockdown and concluded that the level of $PM_{2.5}$ reduced in Mumbai, Delhi, Chennai, Hyderabad, Kolkata from 10–39, 41–53, 19–43, 26–54 and 24–36% respectively, compared to the last five years. The study also showed that the AOD variation results indicated a decreased aerosol level in Chennai, Delhi, Kolkata and Mumbai by 29, 11, 4 and 1% respectively,

Table 1 Impact of COVID-19 lockdown on air contaminants in India

Studied City	Duration of study	Contaminants	Sources of particular pollutants	Impact of lockdown on the source	Remarks	Reference
Delhi	3rd March to 14th April 2020	NO_2, SO_2, CO, $PM_{2.5}$ and PM_{10}	Power plant, vehicle movement, industries, restaurant, administrative centers	Partial restriction on power plants in Delhi region. Reduced vehicle movement and closing of restaurants, industries, administrative centers shops, and many others	NO_2 and CO level were reduced by 52.68 and 30.35%, respectively, during the lockdown period. Both particulate matter concentrations ($PM_{2.5}$ and PM_{10}) declined by > 50%. The reduction in level of SO_2 was 17.97%	Mahato et al. (2020)
22 cities	16th March to 14th April from 2017 to 2020	NO_2, SO_2, CO, PM_{10} and $PM_{2.5}$	Power plants and other human activities	Restrictions on power plants in northern region. But coal powered energy sector continued during lockdown period	Overall, the concentrations of $PM_{2.5}$, PM_{10}, NO_2, and CO declined by 43, 31, 18 and 10%, respectively, during the lockdown period compared to the same period in previous years. A minute change in SO_2 concentration was detected	Sharma et al. (2020)
New Delhi and Lucknow	1st to 21st February and 25th March to 14th April 2020	$PM_{2.5}$, NO_2, SO_2 and CO	Industrial activity, vehicular movements and construction work	Lower industrial activity, transportation, vehicular movements, and construction work	The $PM_{2.5}$ levels in New Delhi before the lockdown ranged between 85–456 μg m^{-3} and after lockdown it was 47 to 204 μg m^{-3}. The concentration of NO_2 in Lucknow City before and after the lockdown ranged from 22–158 μg m^{-3} and 3–59 μg m^{-3}, respectively. The concentration of CO decreased from 15–150 μg m^{-3} to 5–98 μg m^{-3} in New Delhi and 20–199 μg m^{-3} to 3–55 μg m^{-3} in Lucknow	Srivastava et al. (2020)
Delhi	1st January to 31st March 2020	PM_{10}, $PM_{2.5}$, SO_2, NO, NO_2 and CO	Transportation, workplace, traffic	All workplaces and colleges were shutdown. Decline in incomplete combustion in traffic spots from vehicular exhausts	There was a significant reduction of particulate matter and trace gases. $PM_{2.5}$ and PM_{10} declined by 200%	Kotnala et al. (2020)

Table 1 (continued)

Studied City	Duration of study	Contaminants	Sources of particular pollutants	Impact of lockdown on the source	Remarks	Reference
Bengaluru, Delhi, Kolkata and Mumbai	10th to 20th March 2020 and 25thMarch to 6th April 2020	PM_{10}, $PM_{2.5}$, NO_2 and CO	Coal power plants, social and travel restrictions	Shutdown of the coal power plants. The electricity demands declined by ~ 20–30% due to shutdown of educational institutes, railways	Pollutants like $PM_{2.5}$, PM_{10}, NO_2 and CO declined in Mumbai by 32.43, 47, 75 and 46%, Kolkata by 22.41, 34, 60 and 29%; and Bangalore by 22.85, 42, 70 and 38% respectively, during the lockdown period compared to previous years In Delhi the concentration of $PM_{2.5}$, PM_{10}, NO_2 and CO declined by ~ 41, 52, 51 and 28% respectively, in comparison to the before	Jain and Sharma (2020)
Ahmadabad, Chennai, Kolkata, Hyderabad, New Delhi and Mumbai	1st March to 31st May 2020	PM_{10}, $PM_{2.5}$ and NO_2	Public transport, industries, individual activities	Shutdown of mentioned activities	During the lockdown period, the surface air quality improved significantly with clear reduction in all contaminates in all studied cities, The AOD and NO_2 levels declined by about 60 and 45% respectively	Kumar (2020)

Table 2 Impact of COVID-19 lockdown on air contaminants in China

Studied City	Duration of Study	Contaminants	Sources of particular pollutants	Impact of lockdown on the source	Remarks	References
Wuhan	January to February from 2019 and 2020	NO_2	Transport activities	Lower transport activities result in less energy consumption and lower demand of oil	NO_2 emission reduced by 30% during the lockdown period compared to before lockdown	Muhammad et al. (2020)
Hefei, Anqing and Suzhou	January to March from 2017 to 2020	NO_2, SO_2, CO, $PM_{2.5}$ and PM_{10}	Emissions from industries and transportation. Construction work	Restricted traffic, closing factories reduced transportation and industrial emissions. Less use of petrol and diesel vehicles	The average concentration of NO_2, SO_2, CO, $PM_{2.5}$ and PM_{10} decreased by 52.8, 52.5, 36.2, 46.5 and 48.9% respectively, in February and March compared to the same period of 2017–2019	Xu et al. (2020)
44 cities in the Jing-jin-Ji metropolitan circle	1st January and 21st March 2020	NO_2, SO_2, CO, $PM_{2.5}$ and PM_{10}	Travel and human mobility	After implementation of travel bans human mobility dropped by 69.85%	On average the concentrations of NO_2, SO_2, $PM_{2.5}$, PM_{10} and CO decreased by 24.67, 6.76, 5.93,13.66 and 4.58%, respectively during the lockdown period, compared to before lockdown The average AQI was decreased by 7.80%	Bao and Zhang (2020)
Cities in eastern-southeastern parts	1st January to 9th February 2020	NO_2, SO_2, CO, $PM_{2.5}$, PM_{10} and O_3	Transportation and industry sectors	All non-essential factories were shut down and the running of trucks and buses in the Beijing Tianjin-Hebei region and its nearby areas reduced by 77 and 39% respectively	The concentration of NO_2, SO_2 and CO decreased by 19.4 μg m^{-3}, 2.2 μg m^{-3} and 0.23 μg m^{-3}, respectively, compared to before lockdown. The level of $PM_{2.5}$ reduced from 65.0 μg m^{-3} to 51.4 μg m^{-3}. The overall average AQI of all studied stations decrease by 20% (from 89.6 to 71.6) during the control period	Wang et al. (2020)
Wuhan	14th to 25th March 2020	NO_2 and $PM_{2.5}$	Traffic, industrial activity and power plants	Power plants and industry stop their production. The vehicular movement also decline considerably	The level of NO_2 and $PM_{2.5}$ was reduced to 22.8 and 1.4 μg/m^3, respectively during the lockdown period in Wuhan city	Zambrano-Monserrate et al. (2020)

Table 2 (continued)

Studied City	Duration of Study	Contaminants	Sources of particular pollutants	Impact of lockdown on the source	Remarks	References
41 cities of YRD region	January to March from 2017 to 2020	NO_2, SO_2, CO, $PM_{2.5}$ and PM_{10}	Industrial and construction operation. Residential activity includes cooking, waste treatment and residential combustion	Industrial activities halt in various enterprises, eateries construction sites	The concentration of PM_{10}, $PM_{2.5}$, CO, NO_2 and SO_2 declined by 19.6, 12.0, 7.8, 18.5 and 29.3%, respectively compared to the same period of the previous year 2019 During first phase lockdown the reduction in the level of PM_{10}, $PM_{2.5}$, CO, NO_2 and SO_2 was 33.7, 31.8, 20.9, 45.1 and 20.4%, respectfully, and in the second phase lockdown period the concentrations of the same chemicals declined by 29.0, 33.2, 14.7, 25.9, 27.2 and 7.6%, respectively Overall, the concentration of criteria pollutants in the YRD cites region from January to March 2020 was much lower compared to the same period of 2017–2019	Li et al. (2020)
Wuhan	1st January 2017 to 18th April 2020	NO, NO_2, $PM_{2.5}$ and PM_{10}	Transportation	Road and non-road transport reduced drastically	During the lockdown period, the concentration of NO and NO_2 decreased by approximately 63 and 53%, respectively, as compared to before lockdown. The overall concentration of particulate matter was reduced by 43% in the city during the lockdown.	Sicard et al. (2020)

compared to 2019. During the four lockdown periods, the average AOD and NO_2 declined to the maximum level in the Indian region by 60 and 45% compared to the average of 2017–2019 (Kumar et al. 2020).

China

China was the first country that implemented the stringent lockdown as a COVID-19 preventive measure on January 23, 2020 (Muhammad et al. 2020), which helped the country to control the spread of the virus and lighten the load on health facilities (Wilder-Smith and Freedman 2020). Due to the lockdown implementation, the pollution load in the Wuhan area decreased and the quality of air improved. Environmental pollutants such as NO_2, CO, SO_2, and $PM_{2.5}$ were lower during the pandemic periods compared to the same period of time in previous years (Table 2) (Muhammad et al. 2020). Data from the Copernicus Atmosphere Monitoring Service (CAMS) by the European Union showed that about 20–30% of $PM_{2.5}$ decreased in large areas of China in February 2020, compared to the monthly average of February 2017–2019 (Zambrano-Monserrateet al. 2020). During lockdown phase, the carbon emission rate decreased by 25% in China because factories were closed, people stayed at home to maintain social distancing, and coal use was reduced to 40% at power plants compared to the last three months of 2019 (Saadat et al. 2020; Dutheil et al. 2020). Wang and Su (2020) indicated that China's air quality quickly improved during the pandemic and significantly helped to reduce the overall level of global carbon emissions.

Wang et al. (2020) found that the overall AQI of all the studied stations in the eastern and south eastern parts of China, reduced by 30% during the lockdown period. The concentration of air pollutants NO_2, SO_2, CO and $PM_{2.5}$ also decreased during the lockdown period because of the reduction in emissions from industrial and transportation sectors (Table-2). However, the concentration of O_3 at all of the studied stations increased from 39.0 to 59.1 μg m^{-3} during the lockdown period. Xu et al. (2020) found that the average concentration of NO_2, SO_2, CO, $PM_{2.5}$ and PM_{10} of three central China cities (Anqing, Hefei, and Suzhou) decreased in February and March 2020 by 52.8–27.2, 52.5–41.1, 36.2–24.2, 46.5–33.0 and 48.9–25.3% respectively, compared to the same period of 2017–2019. However, the average concentration of O_3 did not change significantly and showed a slight increase by 3.6%. This might be due to the limited reaction of NO and O_3 in conditions of low NO_2 concentration. Among the average AQI values for the 5 days in February 2020, the highest was 122.6, which was 45.1% lower compared to February 2017–2019 when the maximum AQI was 223.2.

Italy

In Italy the first case of COVID-19 was recorded on 20 February 2020 in Codogno, which is 60 km away from Milan (Collivignarelli et al. 2020; Grasselli et al. 2020; Porcheddu et al. 2020). On the very next day, 34 new cases were confirmed in Lombardy. Italy was the first country where the COVID-19 cases increased after the virus originated in China. After that, the government declared that area as a "red zone." By 2nd March 2020, cases increased to 59,183 (WHO 2020), and the administration imposed total lockdown. The restriction measures minimized industrial activities in an unprecedented way, which resulted in improved air quality (Table 3). The pollution levels in terms of NO_2, SO_2, CO, PM_{10}, and $PM_{2.5}$ decreased in many cities of Italy, such as Rome, Milan and Turin (Collivignarelli et al. 2020; Sicard et al. 2020). Collivignarelli et al. (2020) found that the level of NO_2 in Milan was 31.9 ± 1.9 μg m^{-3} during the partial lockdown and 22.1 ± 1.2 μg m^{-3} during the total lockdown, which was lower compared to the control/reference period (53.4 ± 2.6 μg m^{-3}). This clearly showed that the reduction of NO_2 during the lockdown period. The same study also reported that overall SO_2 was reduced by 25.4% during the total lockdown period.

NO and NO_2 levels reduced to a lesser extent in Turin compared to other European cities such as Nice, Rome, and Valencia, because of the continuing activities of essential food and pharmaceutical industries in Turin during the lockdown (Sicard et al. 2020). However, the levels of NO and NO_2 in Turin's high traffic areas, which were the highest contributor to NO_X emission, sharply reduced by ~ 78 and ~ 65% respectively (Sicard et al. 2020). During the lockdown, the concentration of $PM_{2.5}$ and PM_{10} decreased in Turin by 13 and 9%, respectively, but increased in Rome by 11 and 2%, respectively. This increase of particulate matter in Rome may have been due to domestic heating using fossil fuels and garden activities (e.g., burning biomass). However, the level of particulate matter declined greatly in the traffic (gasoline) station of Rome because of lower road and non-road transport and low fuel combustion in nearby commercial and institutional buildings (Sicard et al. 2020). Further, the study reported that the surface O_3 level increased by 14% in Rome and 27% in Turin because of an unprecedented reduction of NO_X emission (http://www-personal.umich.edu/~sillman/ozone.htm).

Brazil

Brazil recorded the first confirmed COVID-19 case on 25 February 2020. After that, the state governor of Rio de Janeiro declared a public health emergency and implemented partial lockdown measures a week later. Dantas et al. (2020) found that on the first day of the lockdown, the concentration

Table 3 Impact of COVID-19 lockdown on air contaminants in Italy

Studied City	Duration of study	Contaminants	Sources of particular pollutants	Impact of lockdown on the source	Remarks	References
Rome, Turin	1st January 2017 to 18th April 2020	NO, NO_2, $PM_{2.5}$, and PM_{10}	Transportation, emission from institutional and commercial buildings	Reduced road and non-road movement and less fuel combustion in nearby institutional and commercial buildings	During the lockdown period, the concentration of NO and NO_2 decreased by approximately 63 and 53%, respectively compared to before lockdown. In Turin, higher reduction of NO (~78%) and NO_2 (~65%) recorded at the traffic stations The level of $PM_{2.5}$ and PM_{10} decreased in Turin by 13 and 9%, respectively and increased in Rome by 11 and 2%, respectively compared to before lockdown. However, in the traffic stations of Rome, $PM_{2.5}$ and PM_{10} reduced by 1–3%	Sicard et al. (2020)
Rome	14th to 25th March 2020	NO_2			The result from the Copernicus Sentinel-5P satellite data showed a significant decline in NO_2 concentration in the city	Zambrano-Monserrate et al. (2020)
Milan	7th to 20th February and 9th March to 5th April 2020	PM_{10}, $PM_{2.5,}$ NO_X, SO_2, CO, BC and benzene	Social movement and production activities	Limitation in public movements. closure of many production activities	The study found a significant reduction in all the mentioned contaminants during the partial and complete lockdown period except SO_2 in comparison to the reference period SO_2 concentration remained unchanged in many studied areas	Collivignarelli et al. (2020)

Table 4 Impact of COVID-19 lockdown on air contaminants in Brazil

Studied City	Duration of study	Contaminants	Sources of particular pollutants	Impact of lockdown on the source	Remarks	References
Rio de Janeiro	2nd March to 16th April 2020	NO_2, CO and PM_{10}	Construction works, industrial activity, transportation and dust resuspension	The fleet of buses partly reduced and passenger car movement decreased by 70–80% in the first lockdown week and again increased by 50%	NO_2 emission median value was lowered to 24.1–32.9%. A significant decline in CO level was observed (30.3–48.5%) due to partial lockdown PM_{10} levels reduced only in the first week of partial lockdown	Dantas et al. (2020)
Rio de Janeiro	1st March to 16th April 2020	NO, NO_2, CO, PM_{10} and O_3	Social and educational activity. transportation	Restaurants, shopping centres, fitness centres, cultural and sporting events, educational activities were closed and canceled. Public transport also reduced	The concentration of NO, NO_2, CO and PM_{10} decreased during the lockdown period compared to pre-lockdown. The level of ozone was increased	Siciliano et al. (2020)
São Paulo	25th February to 20th April 2020	NO, NO_2 and CO	Traffic emissions	Vehicle movement especially heavy-duty diesel trucks decreased considerably	The levels of NO, NO_2, and CO drastically declined by up to 77.3, 54.3 and 64.8%, respectively compared to the five year monthly mean during the partial lockdown	Nakada and Urban (2020)

Table 5 Impact of COVID-19 lockdown on air contaminants in Spain

Studied City	Duration of study	Contaminants	Sources of particular pollutants	Impact of lockdown on the source	Remarks	References
Valencia	1st January 2017 to 18th April 2020	NO, NO_2, $PM_{2.5}$ and PM_{10}	Transportation	Reduction in the road and non-road movement	The concentration of NO and NO_2 decreased by approximately 63 and 53% respectively during the lockdown compared to before lockdown Levels of $PM_{2.5}$ and PM_{10} decreased 13 and 32%, respectively during the lockdown	Sicard et al. (2020)
Madrid	14th to 25th March 2020	NO_2			The Copernicus Sentinel-5P satellite data showed a significant decline in NO_2 concentration in the city	Zambrano-Monserrate et al. (2020)
Barcelona, Madrid and Seville	March 2019 and 2020	NO_2	Transportation	Mobility reduced up to 90%	NO_2 emission decreased by 20–30% in the mentioned cities during the lockdown	Muhammad et al. (2020)
Barcelona	16th February to 30th March 2020	PM_{10}, BC, NO_2 and SO_2	Industrial activity, harbor emissions, construction works, dust resuspension	Restricted social contact, closing of commercial place and administrative centres,	The concentration of PM_{10} in air was reduced by 28 to 31% during two-week lockdown period as compared to before lockdown The BC and NO_2 significantly decreased (by 45 to 51%) during the lockdown period as compared to before lockdown. there was no significant change in the concentration of SO_2	Tobías et al. (2020)

of primary pollutants such as PM_{10}, NO_2, and CO showed a significant decrease. The study used data from the municipal Department of Environment (SMAC) automatic monitoring station to analyze the pollution level in the city. Results of different pollutants varied among different study sites. Interestingly, O_3 concentration increased due to decreased NO_X levels in the atmosphere. In São Paulo state's urban road, NO and NO_2 concentrations (μg m^{-3}) declined by up to 77.3 and 54.3% respectively, while CO levels decreased by up to 64.8% in the city center during the partial lockdown in late March 2020 compared to the last five year monthly mean (Nakada and Urban 2020). The study also found that traffic-related pollutants such as CO and NO_x decreased during the quarantine period (March 24, 2020 to April 20, 2020). However, in São Paulo urban areas, O_3 concentration increased by approximately 30%. During the 90 days quarantine period, the concentrations of $PM_{2.5}$, PM_{10} and NO_2 in São Paulo city dropped by 46, 45 and 58% respectively, compared to the same period in 2019 (Debone et al. 2020). Marinho and Foroutan (2020) analyzed the air quality status of Rio de Janeiro and São Paulo using a compilation of satellite and ground-based data and found that the daily concentration of NO_2 for May 2020 decreased by 18.8 and 13.3% respectively, compared to that of 2019. However, $PM_{2.5}$ concentration of the São Paulo region showed no significant change compared to the same period in 2019 (Table 4).

Spain

The COVID-19 case was first recognized in Spain on 31 January 2020. By mid-March, the total COVID-19 confirmed cases were > 7000, with > 250 deaths. At the end of March, Spain became the third-most affected country with > 85,000 total confirmed cases and > 7000 deaths. Spanish government declared lockdown on 14 March 2020, which restricted free movement, stopped business activities, and reduced public transportation (Tobías et al. 2020). This lockdown helped in controlling the coronavirus and in reducing urban air pollution in many cities (Table 5). The concentration of major air pollutants such as NO, NO_2, PM_{10}, and $PM_{2.5}$ were reduced in Barcelona, Madrid, Valencia, and Seville during the lockdown period (Sicard et al. 2020; Muhammad et al. 2020; Tobías et al. 2020; Zambrano-Monserrate et al. 2020). In Barcelona, the PM_{10} average concentration decreased in urban and traffic stations by 28 and 31%, respectively during the 14-day lockdown compared to before lockdown (Tobías et al. 2020). During the lockdown period the average NO_2 loads detected by the tropospheric monitoring instrument (TROPOMI) over the Barcelona metropolitan area decreased by 57% compared to before lockdown. O_3 concentration increased by 29% at Barcelona urban stations. Sicard et al. (2020) stated that the concentration of PM_{10} and $PM_{2.5}$ significantly decreased at traffic stations in Valencia by 51.3

Table 6 Impact of COVID-19 lockdown on air contaminants in France

Studied City	Duration of study	Contaminants	Sources of particular pollutants	Impact of lockdown on the source	Remarks	References
Paris	14th to 25th March 2020	NO_2		Implement strict quarantine measures	The result from the Copernicus Sentinel-5P satellite data shows a significant decline in NO_2 concentration in the city	Zambrano-Monserrate et al. (2020)
Nice	1st January 2017 to 18th April 2020	NO, NO_2, $PM_{2.5}$ and PM_{10}	Transportation	Reduction in the road and non-road movement	The concentration of NO and NO_2 decreased by approximately 63 and 53%, respectively, during the lockdown compared to before lockdown $PM_{2.5}$ and PM_{10} were reduced by 3 and 6%, respectively	Sicard et al. (2020)
Paris and other major cities	March 2019 and 2020	NO_2	Transportation	Mobility reduced up to 90%	Noticeable reduction in the emission of NO_2 was observed across the cities due to shut-down in transportation	Muhammad et al. (2020)

Table 7 Impact of COVID-19 lockdown on air contaminants in the USA

Studied City	Duration of Study	Contaminants	Sources of particular pollutants	Impact of lockdown on the source	Remarks	References
Majority of US states	April 2015 to 2020	$PM_{2.5}$ and NO_2	Business activity, transportation	Reduction in passenger vehicle NO_2 emissions	NO_2 concentration declined significantly in 65% of the monitoring sites with an average drop by 2 ppb while $PM_{2.5}$ concentration not reduced significantly compared to the last five years	Archer et al. (2020)
Los Angeles, New York, Chicago, Phoenix, San Diego, Philadelphia, San Antonio, and San Jose	January 15, 2020 to May 4, 2020	$PM_{2.5}$			The overall study suggested that lockdown reduced the environmental pressure of big cities in the US	Pata (2020)
North-eastern part	March 2015 to 2019 and March 2020	NO_2			By investigating the image captured by NASA via the AURA satellite using the OMI instrument it was observed that emissions of NO_2 declined by up to 30% due to lockdown	Muhammad et al. (2020)
New York	January to May from 2015 to 2020	$PM_{2.5}$ and NO_2	Transportation	Social distancing and shutdown	$PM_{2.5}$ and NO_2 concentrations declined by 36 and 51% respectively immediately after the shutdown	Zangari et al. (2020)

Table 8 Impact of COVID-19 lockdown on air contaminants in other countries

Country	Studied City	Duration of study	Contaminants	Sources of particular pollutants	Impact of lockdown on the source	Remarks	References
UAE	Abu Dhabi	March 2019 and March 2020	$PM_{2.5}$	Travelling, Transportation	Restrictions on commercial flights, vehicles and ban of commercial activities	The concentration of $PM_{2.5}$ decreased by 32.4% during the lockdown period compared to the same month of the previous year	Shrestha et al. (2020)
Kazakhstan	Almaty	2nd March to 14th April 2020	$PM_{2.5}$, NO_2, SO_2 and CO	Transportation	Reduction in traffic load	$PM_{2.5}$ concentration was 31 μg m^{-3} during the lockdown period, which is lower than the concentrations in 2019 (40 μg m^{-3}) and 2018 (38 μg m^{-3}) NO_2 and CO concentration substantially declined by 49 and 35%, respectively, compared to before lockdown, while SO_2 level increased by 7%	Kerimray et al. (2020)
Iran	Tehran	21st March to 21st April 2019 and 2020	PM_{10}, $PM_{2.5}$, NO_2, SO_2 and CO	Transportation, industrial activity	Lower traffic emissions. Closing of educational institutes and companies	The concentration of PM_{10}, NO_2, SO_2 and CO decreased with spatial variation of 1.4–30, 1–30%, 5–28 and 5–4% respectively, while the concentration of $PM_{2.5}$ and O_3 increased by 2–50% and 0.5–103% compared to previous year	Broomandi et al. (2020)
Mongolia	Ulaanbaatar	March 2019 and March 2020	PM_{10} and $PM_{2.5}$	Transportation	Restricted traveling and commercial activities	The concentration of PM_{10} and $PM_{2.5}$ declined by 43.4 and 25.6%, respectively, during the lockdown period	Shrestha et al. (2020)

Table 8 (continued)

Country	Studied City	Duration of study	Contaminants	Sources of particular pollutants	Impact of lockdown on the source	Remarks	References
Morocco	Salé City	11th March to 2nd April 2020	PM_{10}, NO_2 and SO_2	Industrial and transportation activities	Industrial and transportation activities were stopped which reduced the emissions	Levels of PM_{10}, NO_2 and SO_2 decreased from 114.6–28. 3 μg m^{-3} to 5.6–0.2 μg m^{-3} and 6.6–3.3 μg m^{-3} respectively, during the lockdown period, which corresponds to a decline of 75, 96 and 49%, respectively.	Otmani et al. (2020)
Norway	Oslo	March 2019 and March 2020	NO_2	Transportation	Restricted traveling and commercial activities	Levels of NO_2 declined by 39.7% during the lock down period	Shrestha et al. (2020)
Switzerland	Bern	March 2019 and March 2020	NO_2	Travelling, Transportation	Restricted traveling and commercial activities	The concentration of NO_2 decreased by 19.1% during the lockdown period	Shrestha et al. (2020)
Australia	Sydney	March 2019 and March 2020	$PM_{2.5}$	Travelling, Transportation	Restricted traveling and commercial activities	The concentration of $PM_{2.5}$ decreased by 35% during the restriction period compared to the same month of the previous year	Shrestha et al. (2020)
Peru	Lima	March 2019 and March 2020	PM_{10}, NO_2 and SO_2	Travelling, Transportation	Restricted traveling and commercial activities	Concentrations PM_{10} and SO_2 decreased by 25.7 and 60% respectively, during the lockdown month compared to the same month of the previous year. NO_2 levels significantly declined during the lockdown period	Shrestha et al. (2020)

and 29.3% respectively. The concentrations of NO, NO_2, CO and PM_{10} were reduced significantly; however, the level of ozone increased in Rio de Janeiro (Siciliano et al. 2020).

France

France detected its first COVID-19 case on 24 January 2020 and cluster of cases were identified first in Haute Savoie on 8 February 2020 and then in Oise, and Brittany (Stoecklin et al. 2020; Roux et al. 2020). In Europe, France was the most COVID-19 impacted country after Spain, Italy and Germany. By November 05, 2021, more than 6,966,140 confirmed cases of COVID-19 were recorded in the country. To lower the impact of the virus, the French government declared full lockdown on 17 March 2020 (Roux et al. 2020; Salje et al. 2020). After the beginning of the lockdown, the air quality of cities improved during the restriction period (Table 6). In France, NO, NO_2, and particulate matter concentration decreased significantly in Paris, Nice, and other major cities during the lockdown period compared to before lockdown (Muhammad et al. 2020; Sicard et al. 2020; Zambrano-Monserrate et al. 2020). $PM_{2.5}$ and PM_{10} concentrations declined at traffic stations in Nice by 8 and 7.6%, respectively due to reduction of road and non-road transport during the lockdown period (Sicard et al. 2020). These findings indicated that there was an increase in surface ozone levels by 24% in Nice during the lockdown period compared to before lockdown, because of the unprecedented reduction of NO_X emission.

United States

The United States (US) reported its first confirmed case of COVID-19 on 20 January 2020 (Holshve 2020). With ensuing increase in COVID-19 cases, most of the States declared some level of social distancing by mid of March 2020 and compulsory quarantine for COVID-19 diagnosed people or those showing similar symptoms (Archer et al. 2020). By the first week of April, all States imposed lockdown (Mervosh and Swales 2020). Despite the strict measures taken by the government, the US has the highest number of COVID-19 cases in comparison to any other country in the world. As of November 5, 2021, there have been 45,968,940 confirmed cases and 744,398 deaths. During the lockdown and social distancing period, there was a drastic reduction in personal mobility and transportation (Gao et al. 2020). Nationwide, the number of personal vehicles and flight movement decreased by approximately 46 and 13%, respectively (Pishue 2020). Road transport vehicles and airports are the major sources of NO_2 pollution (Archer et al. 2020). Several studies reported decline of various pollutants for this period (Table 7). The concentration of NO_2 declined by 25.5%, with an absolute decrease of 4.8 ppb during the lockdown period (Berman and Ebisu 2020). The concentration of $PM_{2.5}$ also declined during the same period compared to previous years (2017–2019). Another study from New York City recorded decreases in $PM_{2.5}$ and NO_2 levels by 36 and 51%, respectively, immediately after the shutdown. However, analysis through linear time lag model showed no significant difference comparing the same period between 2015 and 2019 (Zangari et al. 2020). Archer et al. (2020) found that more than 65% of the monitoring sites in the US recorded a significant decline in NO_2 concentration compared to the previous five year means, with an average drop of 2 ppb.

Other countries (Germany, Netherlands, Kazakhstan, Mongolia, Morocco, Peru, Australia, Iran, UAE, Norway, Austria, Portugal, Czech Republic and Switzerland)

The coronavirus has spread quickly; therefore, many countries implemented preventive lockdown measures to reduce its impact. Menut et al. (2020) reported that the concentration of NO_2 reduced by 15 to 30%, respectively for Germany and the Netherlands, while in Austria, Portugal and the Czech Republic, concentration declined by an average of 35–45% during the lockdown period as compared to the previous year. In Sydney (Australia) and Abu Dhabi (UAE), the level of $PM_{2.5}$ decreased by 35 and 32.4% respectively, during the lockdown period compared to similar months in previous years (Shrestha et al. 2020). The same study recorded that the level of NO_2 declined in Oslo (Norway) and Bern (Switzerland) by 39.7 and 19.1% respectively, during the lockdown period. Tehran (capital of Iran) recorded a lower concentration of PM_{10}, NO_2, SO_2, and CO during the COVID-19 restriction period compared to the previous year (Broomandi et al. 2020). Kanniah et al. (2020) reported from Malaysia that the lockdown contributed to a 27–30% decline of tropospheric NO_2, a noticeable decrease in AOD over the Southeast Asia region, and decreased pollution outflow over the oceanic areas in Malaysia. During the lockdown period the concentration of PM_{10}, $PM_{2.5}$, NO_2, SO_2, and CO were reduced by 26–31, 23–32, 63–64, 9–20, and 25–31% respectively, in the urban area of Malaysia compared to the same period in 2019 and 2018. In Almaty, Kazakhstan, the concentrations of $PM_{2.5}$, NO_2 and CO declined substantially; however, the concentration of O_3 increased by 15% during the lockdown period (Kerimray et al. 2020). Otmani et al. (2020) reported that the concentrations of NO_2, SO_2, and $PM_{2.5}$ in the city of Sale, Morocco declined during the 10 day lockdown period. Industrial and vehicle emissions declined significantly during this period and thus helped in lowering of those pollutants. Shrestha et al. (2020) found that NO_2 and CO concentrations significantly declined after the lockdown in Amsterdam, Bogota, Sao Paulo, and San Francisco. The levels of PM_s, NO_2, and CO declined in major world cities due to the implementation of lockdown almost at the same time period (Table 8).

Future prospects and recommendations

A global health emergency/crisis was witnessed with the onset of the CP and that is still continuing. The CP has severely impacted the economy. However, it has led to positive impacts on the environment, especially air and water pollution that can be taken as an inspiration and example for behavioral changes required, which can be helpful to handle future environmental pollution-related problems. The increased concentration of environmental pollutants correlate with the increasingly high rates of COVID-19 infection, levels of transmission, and mortality rate. Fifty-five capital provinces of Italy recorded associated changes in air pollution levels with increase in symptomatic COVID-19 cases (Coccia 2020). In the US, with an increase of 1 $\mu g\ m^{-3}$ in the long-term average $PM_{2.5}$, 11% increase in COVID-19 mortality rate occurred (Wu et al. 2020). Debone et al. (2020) predicted that the reduction of air contaminants and the improvement of air quality prevented or avoided 78,377 COVID-19 cases and 387 premature deaths in Brazil. Air quality should therefore be considered as an integral part of the protection and prevention of public health that breaks the spread of similar diseases. The COVID-19 pandemic related lockdown highlighted and showed that the levels of contaminants have a direct relationship with the major economic activities that include industrial activities, energy generation sectors, transportation, and other small and large activities in cities. From this, it is confirmed that moving to more environmentally favorable energy options can lead to lower pollution loads. Governments, policymakers, and individuals should work collaboratively to introduce stringent policies to maintain a healthy and sustainable environment for the future so as to reduce the impacts of such pandemics.

Conclusion

Implementation of rigorous lockdown in response to the CP resulted in the ban of public and personal transport and industrial activities. During lockdown, global environmental pollution levels significantly improved. The level of major air contaminants like NO_2, SO_2, CO, PM ($PM_{2.5}$ and PM_{10}) declined sharply during lockdown in major countries of the world. The lockdown not only effectively restricted the mass scale spread of coronavirus but also significantly reduced major air contaminants and thus prevented severe COVID-19 cases due to decreased lung and breathing complications. In many countries, this type of reduction in air pollution was unprecedented.

Acknowledgements Amit Kumar is thankful to Botany Department, University of Lucknow, Lukcnow.

References

Achakulwisut P, Brauer M, Hystad P, Anenberg SC (2019) Global, national, and urban burdens of paediatric asthma incidence attributable to ambient NO_2 pollution: estimates from global datasets. Lancet Planet Health 3(4):e166–e178

Ankit, Kumar A, Jain V, Deovanshi A, Lepcha A, Das C, Bauddh K, Srivastava S (2021) Environmental impact of COVID-19 pandemic: more negatives than positives. Environ Sust 4:47–454

Archer CL, Cervone G, Golbazi M, Al Fahel N, Hulquist C (2020) Changes in air quality and human mobility in the USA during the COVID-19 pandemic. Bull Atmos Sci Technol 1:491–514. https://doi.org/10.1007/s42865-020-00019-0

Bao R, Zhang A (2020) Does lockdown reduce air pollution? Evidence from 44 cities in northern China. Sci Total Environ 731:139052. https://doi.org/10.1016/j.scitotenv.2020.139052

Berman JD, Ebisu K (2020) Changes in US air pollution during the COVID-19 pandemic. Sci Total Environ 739:139864. https://doi.org/10.1016/j.scitotenv.2020.139864

Braga F, Scarpa GM, Brando VE, Manfè G, Zaggia L (2020) COVID-19 lockdown measures reveal human impact on water transparency in the Venice Lagoon. Sci Total Environ 736:139612. https://doi.org/10.1016/j.scitotenv.2020.139612

Broomandi P, Karaca F, Nikfal A, Jahanbakhshi A, TamjidiM KJR (2020) Impact of COVID-19 event on the air quality in Iran. Aerosol Air Qual Res 20(8):1793–1804. https://doi.org/10.4209/aaqr.2020.05.0205

Burnett R, Chen H, Szyszkowicz M, Fann N, Hubbell B, Pope CA et al (2018) Global estimates of mortality associated with long-term exposure to outdoor fine particulate matter. Proc Natl Acad Sci 115(38):9592–9597

CDC 2020. https://www.cdc.gov/coronavirus/2019-ncov/global-covid-19/world-map.html

Chakraborty I, Maity P (2020) COVID-19 outbreak: migration, effects on society, global environment and prevention. Sci Total Environ 728:138882. https://doi.org/10.1016/j.scitotenv.2020.138882

Coccia M (2020) Factors determining the diffusion of COVID-19 and suggested strategy to prevent future accelerated viral infectivity similar to COVID. Sci Total Environ 729:138474

Collivignarelli MC, Abbà A, Bertanza G, Pedrazzani R, Ricciardi P, Miino MC (2020) Lockdown for CoViD-2019 in Milan: what are the effects on air quality? Sci Total Environ 732:139280. https://doi.org/10.1016/j.scitotenv.2020:139280

Copat C, Cristaldi A, Fiore M, Grasso A, Zuccarello P, Santo SS et al (2020) The role of air pollution (PM and NO2) in COVID-19 spread and lethality: a systematic review. Environ Res. https://doi.org/10.1016/j.envres.2020.110129

Central Pollution Control Board, New Delhi, (2020) https://app.cpcbccr.com/AQI_India/

Dantas G, Siciliano B, França BB, da Silva CM, Arbilla G (2020) The impact of COVID-19 partial lockdown on the air quality of the city of Rio de Janeiro. Brazil. Sci Total Environ 729:139085. https://doi.org/10.1016/j.scitotenv.2020.139085

Debone D, Mariana VC (2020) Simone GEKM (2020) 90 days of COVID-19 social distancing and its impacts on air quality and health in Sao Paulo. Brazil Sustain 12(18):7440

Dutheil F, Baker JS, Navel V (2020) COVID-19 as a factor influencing air pollution? Environ Pollut 263:114466. https://doi.org/10.1016/j.envpol.2020.114466

ESA (2020) https://www.esa.int/Applications/Observing_the_Earth/Copernicus/Sentinel-5P/COVID-19_nitrogen_dioxide_over_China

Gao S, Rao J, Kang Y, Liang Y, Kruse J (2020) Mapping county-level mobility pattern changes in the United States in response to COVID-19. SIGSPATIAL Special 12(1):16–26

Gautam S (2020a) The influence of COVID-19 on air quality in India: a boon or inutile. B Environ Contam Tox 104:724–726. https://doi.org/10.1007/s00128-020-02877-y

Gautam S (2020b) COVID-19: air pollution remains low as people stay at home. Air Qual Atmos Hlth 13:853–857. https://doi.org/10.1007/s11869-020-00842-6

Global Carbon Project 2020. https://www.globalcarbonproject.org/carbonbudget/index.htm

Grasselli G, Pesenti A, Cecconi M (2020) Critical care utilization for the COVID-19 outbreak in Lombardy, Italy. JAMA. https://doi.org/10.1001/jama.2020.4031

Holshue ML, De Bolt C, Lindquist S, Lofy KH, Wiesman J, Bruce H et al (2020) First case of 2019 novel coronavirus in the United States. N Engl J Med 382(10):929–936. https://doi.org/10.1056/NEJMoa2001191

Huang C, Wang Y, Li X, Ren L, Zhao J, Hu Y et al (2020) Clinical features of patients infected with 2019 novel coronavirus in Wuhan, China. Lancet 395:497–506. https://doi.org/10.1016/S0140-6736(20)30183-5

Jain S, Sharma T (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. Aerosol Air Qual Res 20:1222–1236

Ju MJ, Oh J, Choi YH (2021) Changes in air pollution levels after COVID-19 outbreak in Korea. Sci Total Environ 750:141521

Kanniah KD, Zaman NAFK, Kaskaoutis DG, Latif MT (2020) COVID-19's impact on the atmospheric environment in the Southeast Asia region. Sci Total Environ 736:139658. https://doi.org/10.1016/j.scitotenv.2020.139658

Kerimray A, Baimatova N, Ibragimova OP, Bukenov B, Kenessov B, PlotitsynP KF (2020) Assessing air quality changes in large cities during COVID-19 lockdowns: the impacts of traffic-free urban conditions in Almaty. Kazakhstan Sci Total Environ 730:139179. https://doi.org/10.1016/j.scitotenv.2020.139179

Kotnala G, Mandal TK, Sharma SK, Kotnala RK (2020) Emergence of Blue Sky Over Delhi Due to Coronavirus Disease (COVID-19) Lockdown Implications. Aerosol Sci Eng. https://doi.org/10.1007/s41810-020-00062-6

Kumar S (2020) Effect of meteorological parameters on spread of COVID-19 in India and air quality during lockdown. Sci Total Environ 745:141021

Kumar P, Hama S, Omidvarborna H, Sharma A, Sahani J, Abhijith KV et al (2020) Temporary reduction in fine particulate matter due to 'anthropogenic emissions switch-off' during COVID-19 lockdown in Indian cities. Sustain Cities Soc 62:102382. https://doi.org/10.1016/j.scs.2020.102382

Le Quéré C, Jackson RB, Jones MW, Smith AJ, Abernethy S, Andrew RM et al (2020) Temporary reduction in daily global CO_2 emissions during the COVID-19 forced confinement. Nat Clim Chang 10:647–653. https://doi.org/10.1038/s41558-020-0797-x

Lelieveld J, Pozzer A, Pöschl U, Fnais M, Haines A, Münzel T (2020) Loss of life expectancy from air pollution compared to other risk factors: a worldwide perspective. Cardiovasc Res 116(7):1334

Li L, Li Q, Huang L, Wang Q, Zhu A, Xu J 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. Sci Total Environ 732:139282. https://doi.org/10.1016/j.scitotenv.2020.139282

Long NJ (2020) From social distancing to social containment: reimagining sociality for the coronavirus pandemic. Med Anthropol Theory ISSN 2405–691X

Mahato S, Pal S, Ghosh KG (2020) Effect of lockdown amid COVID-19 pandemic on air quality of the megacity Delhi. India Sci Total Environ 730:139086. https://doi.org/10.1016/j.scitotenv.2020.139086

Mandal I, Pal S (2020) COVID-19 pandemic persuaded lockdown effects on environment over stone quarrying and crushing areas. Sci Total Environ 732:139281. https://doi.org/10.1016/j.scitotenv.2020.139281

Marinho RCBF, Foroutan H (2020) Atmospheric pollutant levels in Southeast Brazil during COVID-19 lockdown: combined satellite and ground-based data analysis. In AGU Fall Meeting 2020. AGU

Marquès M, Domingo JL (2021) Positive association between outdoor air pollution and the incidence and severity of COVID-19. A review of the recent scientific evidences. Environ Res 111930

Menut L, Bessagnet B, Siour G, Mailler S, Pennel R, Cholakian A (2020) Impact of lockdown measures to combat Covid-19 on air quality over western Europe. Sci Total Environ 741:140426. https://doi.org/10.1016/j.scitotenv.2020.140426

Mervosh S, Lu D, Swales V (2020) See which states and cities have told residents to stay at home. https://www.nytimes.com/interactive/2020/us/coronavirus-stay-at-home-order.html

Mostafa MK, Gamal G, Wafiq A (2021) The impact of COVID 19 on air pollution levels and other environmental indicators—a case study of Egypt. J Environ Manage 277:111496

Muhammad S, Long X, Salman M (2020) COVID-19 pandemic and environmental pollution: a blessing in disguise? Sci Total Environ 728:138820. https://doi.org/10.1016/j.scitotenv.2020.138820

Nakada LYK, Urban RC (2020) COVID-19 pandemic: Impacts on the air quality during the partial lockdown in São Paulo state, Brazil. Sci Total Environ 730:139087. https://doi.org/10.1016/j.scitotenv.2020.139087

National Aeronautics Space Administration (NASA) (2020)https://earthobservatory.nasa.gov/images

Otmani A, Benchrif A, Tahri M, Bounakhla M, El Bouch M, Krombi MH (2020) Impact of Covid-19 lockdown on PM10, SO2 and NO2 concentrations in Salé City (Morocco). Sci Total Environ 735:139541. https://doi.org/10.1016/j.scitotenv.2020.139541

Pata UK (2020) How is COVID-19 affecting environmental pollution in US cities? Evidence from asymmetric Fourier causality test. Air Qual Atmos Hlth 13:1149–1155. https://doi.org/10.1007/s11869-020-00877-9

Pishue B (2020) COVID-19's impact on freight: an analysis of long-haul freight movement during a pandemic. INRIX Research

Porcheddu R, Serra C, Kelvin D, Kelvin N, Rubino S (2020) Similarity in case fatality rates (CFR) of COVID-19/SARS-COV-2 in Italy and China. J Infect Dev Ctries 14:125–128. https://doi.org/10.3855/jidc.12600

Roux J, Massonnaud C, Crépey P (2020) COVID-19: One-month impact of the French lockdown on the epidemic burden. medRxiv. https://doi.org/10.1101/2020.04.22.20075705

Saadat S, Rawtani D, Hussain CM (2020) Environmental perspective of COVID-19. Sci Total Environ 728:138870. https://doi.org/10.1016/j.scitotenv.2020.138870

Salje H, Kiem CT, Lefrancq N, Courtejoie N, Bosetti P, Paireau J et al (2020) Estimating the burden of SARS-CoV-2 in France. Science 369(6500):208–211

Sarmadi M, Moghanddam VK, Dickerson AS, Martelletti L (2020) Association of COVID-19 distribution with air quality, sociodemographic factors, and comorbidities: an ecological study of US states. Air Qual Atmos Health. https://doi.org/10.1007/s11869-020-00949-w

Shakoor A, Chen X, Farooq TH, Shahzad U, Ashraf F, Rehman A et al (2020) Fluctuations in environmental pollutants and air quality

during the lockdown in the USA and China: two sides of COVID-19 pandemic. Air Qual Atmos Health 13(11):1335–1342
Sharma S, Zhang M, Gao J, Zhang H, Kota SH (2020) Effect of restricted emissions during COVID-19 on air quality in India. Sci Total Environ 728:138878. https://doi.org/10.1016/j.scitotenv.2020.138878
Shrestha AM, Shrestha UB, Sharma R, Bhattarai S, Tran HNT, Rupakheti M (2020) Lockdown caused by COVID-19 pandemic reduces air pollution in cities worldwide. Preprint.https://doi.org/10.31223/osf.io/edt4j
Sicard P, De Marco A, Agathokleous E, Feng Z, Xu X, Paoletti E et al (2020) Amplified ozone pollution in cities during the COVID-19 lockdown. Sci Total Environ 735:139542. https://doi.org/10.1016/j.scitotenv.2020.139542
Siciliano B, Dantas G, da Silva CM, Arbilla G (2020) Increased ozone levels during the COVID-19 lockdown: analysis for the city of Rio de Janeiro, Brazil. Sci Total Environ 737:139765. https://doi.org/10.1016/j.scitotenv.2020.139765
Singh RP, Chauhan A (2020) Impact of lockdown on air quality in India during COVID-19 pandemic. Air Qual Atmos13:921–928 Health. https://doi.org/10.1007/s11869-020-00863-1
Son JY, Fong KC, Heo S, Kim H, Lim CC, Bell ML (2020) Reductions in mortality resulting from reduced air pollution levels due to COVID-19 mitigation measures. Sci Total Environ 744:141012
Srivastava S, Kumar A, Bauddh K, Gautam AS, Kumar S (2020) 21-day lockdown in India dramatically reduces air pollution indices in Lucknow and New Delhi, India. B Environ Contam Tox. https://doi.org/10.1007/s00128-020-02895-w
Stoecklin SB, Rolland P, Silue Y, Mailles A, Campese C, Simondon A et al (2020) First cases of coronavirus disease 2019 (COVID-19) in France: surveillance, investigations and control measures, January 2020. Euro Surveill 25(6):2000094. https://doi.org/10.2807/1560-7917.ES.2020.25.6.2000094
Tobías A, Carnerero C, Reche C, Massagué J, Via M, Minguillón MC et al (2020) Changes in air quality during the lockdown in Barcelona (Spain) one month into the SARS-CoV-2 epidemic. Sci Total Environ 726:138540. https://doi.org/10.1016/j.scitotenv.2020.138540
Wang Q, Su M (2020) A preliminary assessment of the impact of COVID-19 on environment—a case study of China. Sci Total Environ 728:138915. https://doi.org/10.1016/j.scitotenv.2020.138915
Wang Y, Yuan Y, Wang Q, Liu C, Zhi Q, Cao J (2020) Changes in air quality related to the control of coronavirus in China: Implications for traffic and industrial emissions. Sci Total Environ 731:139133. https://doi.org/10.1016/j.scitotenv.2020.139133
WHO (2006) In: Prüss-Üstün A, Corvalán C (Eds) Preventing Disease Through Healthy Environments-Towards an Estimate of the Environmental Burden of Disease. ISBN: 92 4 159382 2
WHO (2020) WHO. http://www.who.int
WHO (2021) WHO. http://www.who.int
Wilder-Smith A, Freedman DO (2020) Isolation, quarantine, social distancing and community containment: pivotal role for old-style public health measures in the novel coronavirus (2019-nCoV) outbreak. J Travel Med 27(2):1–4. https://doi.org/10.1093/jtm/taaa020
Wu X, Nethery RC, Sabath MB, Braun D, Dominici F (2020) Air pollution and COVID-19 mortality in the United States: strengths and limitations of an ecological regression analysis. Sci Adv 6(45):eabd4049
Xu K, Cui K, Young LH, Wang YF, Hsieh YK, Wan S, Zhang J (2020) Air quality index, indicatory air pollutants and impact of COVID-19 event on the air quality near Central China. Aerosol Air Qual Res 20:1204–1221. https://doi.org/10.4209/aaqr.2020.04.0139
Yunus AP, Masago Y, Hijioka Y (2020) COVID-19 and surface water quality: improved lake water quality during the lockdown. Sci Total Environ 731:139012. https://doi.org/10.1016/j.scitotenv.2020.139012
Zambrano-Monserrate MA, Ruano MA, Sanchez-Alcalde L (2020) Indirect effects of COVID-19 on the environment. Sci Total Environ 728:138813. https://doi.org/10.1016/j.scitotenv.2020.138813
Zangari S, Hill DT, Charette AT, Mirowsky JE (2020) Air quality changes in New York City during the COVID-19 pandemic. Sci Total Environ 742:140496. https://doi.org/10.1016/j.scitotenv.2020.140496