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

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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 (NO2), sulphur dioxide (SO2), 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 NO2 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 PM2.5 and ozone (O3) causes ~ 8.8 million excess deaths yearly, while NO2 is responsible for 4 million new pediatric asthma cases every year (Burnett et al. 2018; Achakulwisut...
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 PM2.5, PM10, NO2, CO and SO2. 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 (CO2), methane (CH4), 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 NO2, CO2, CO, SO2, PM10, and PM2.5 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 NO2 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 NO2 and CO decreased by 52.68% and 30.35% respectively during the lockdown period. The concentration of PM10 and PM2.5 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 PM2.5 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 PM2.5 from 85 to 456 μg m−3 (before lockdown) to 47–204 μg m−3 (after lockdown). The concentrations of NO2 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 O3 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 PM10 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 PM2.5 up to fourth phase lockdown and concluded that the level of PM2.5 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,
| 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           | NO₂, SO₂, CO, PM₂.₅ and PM₁₀ | 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 | NO₂ and CO level were reduced by 52.68 and 30.35%, respectively, during the lockdown period. Both particulate matter concentrations (PM₂.₅ and PM₁₀) declined by > 50%. The reduction in level of SO₂ was 17.97% | Mahato et al. (2020)         |
| 22 cities            | 16th March to 14th April from 2017 to 2020 | NO₂, SO₂, CO, PM₁₀ and PM₂.₅ | 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 PM₂.₅, PM₁₀, NO₂ 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 SO₂ concentration was detected | Sharma et al. (2020)        |
| New Delhi and Lucknow | 1st to 21st February and 25th March to 14th April 2020 | PM₂.₅, NO₂, SO₂ and CO | Industrial activity, vehicular movements and construction work                                     | Lower industrial activity, transportation, vehicular movements, and construction work            | The PM₁₀ 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 NO₂ 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         | PM₁₀, PM₂.₅, SO₂, NO, NO₂ 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. PM₂.₅ and PM₁₀ 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 25th March 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 | 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 | NO₂                           | Transport activities                                      | Lower transport activities result in less energy consumption and lower demand of oil             | NO₂ 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  | NO₂, SO₂, CO, PM_{2.5} and PM_{3.0} | 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 NO₂, SO₂, CO, PM_{2.5} and PM_{3.0} 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 Jingjin-Ji metropolitan circle | 1st January and 21st March 2020 | NO₂, SO₂, CO, PM_{2.5} and PM_{3.0} | Travel and human mobility                                | After implementation of travel bans human mobility dropped by 69.85%                          | On average the concentrations of NO₂, SO₂, 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 | Bao and Zhang (2020)             |
| Cities in eastern-southeastern parts | 1st January to 9th February 2020   | NO₂, SO₂, CO, PM_{2.5}, PM_{3.0} and O₃ | 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 NO₂, SO₂, 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            | NO₂ 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 NO₂ and PM_{2.5} was reduced to 22.8 and 1.4 μg/m³, respectively during the lockdown period in Wuhan city | Zambrano-Monserrate et al. (2020) |
| 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 | NO₂, SO₂, CO, PM₂.₅ and PM₁₀ | 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 PM₁₀, PM₂.₅, CO, NOₓ and SO₂ 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 PM₁₀, PM₂.₅, CO, NOₓ and SO₂ was 33.7, 31.8, 20.9, 45.1 and 20.4%, respectively, 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 | NOₓ, NO₂, PM₂.₅ and PM₁₀ | Transportation                                                                                     | Road and non-road transport reduced drastically                                               | During the lockdown period, the concentration of NO and NO₂ 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\textsubscript{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\textsubscript{2}, CO, SO\textsubscript{2}, and PM\textsubscript{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\textsubscript{2.5} decreased in large areas of China in February 2020, compared to the monthly average of February 2017–2019 (Zambrano-Monserrate et 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\textsubscript{2}, SO\textsubscript{2}, CO and PM\textsubscript{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\textsubscript{3} at all of the studied stations increased from 39.0 to 59.1 μg m\textsuperscript{-3} during the lockdown period. Xu et al. (2020) found that the average concentration of NO\textsubscript{2}, SO\textsubscript{2}, CO, PM\textsubscript{2.5} and PM\textsubscript{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\textsubscript{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\textsubscript{3} in conditions of low NO\textsubscript{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\textsubscript{2}, SO\textsubscript{2}, CO, PM\textsubscript{10}, and PM\textsubscript{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\textsubscript{3} in Milan was 31.9 ± 1.9 μg m\textsuperscript{-3} during the partial lockdown and 22.1 ± 1.2 μg m\textsuperscript{-3} during the total lockdown, which was lower compared to the control/reference period (53.4 ± 2.6 μg m\textsuperscript{-3}). This clearly showed that the reduction of NO\textsubscript{2} during the lockdown period. The same study also reported that overall SO\textsubscript{2} was reduced by 25.4% during the total lockdown period.

NO and NO\textsubscript{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\textsubscript{3} in Turin’s high traffic areas, which were the highest contributor to NO\textsubscript{x} emission, sharply reduced by ~78 and ~65% respectively (Sicard et al. 2020). During the lockdown, the concentration of PM\textsubscript{2.5} and PM\textsubscript{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\textsubscript{3} level increased by 14% in Rome and 27% in Turin because of an unprecedented reduction of NO\textsubscript{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, NO₂, 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 NO₂ decreased by approximately 63 and 53%, respectively compared to before lockdown. In Turin, higher reduction of NO (~78%) and NO₂ (~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 | NO₂                      | Social movement and production activities                                                        | Limitation in public movements, closure of many production activities                           | The result from the Copernicus Sentinel-5P satellite data showed a significant decline in NO₂ concentration in the city | Zambrano-Monserrate et al. (2020) |
| Milan       | 7th to 20th February and 9th March to 5th April 2020 | PM$_{10}$, PM$_{2.5}$, NOₓ, SO₂, 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 SO₂ in comparison to the reference period. SO₂ 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 | NO₂, CO and PM₁₀ | 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% | NO₂ 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 PM₁₀ levels reduced only in the first week of partial lockdown | Dantas et al. (2020) |
| Rio de Janeiro | 1st March to 16th April 2020 | NO, NO₂, CO, PM₁₀ and O₃ | 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, NO₂, CO and PM₁₀ 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, NO₂ and CO | Traffic emissions | Vehicle movement especially heavy-duty diesel trucks decreased considerably | The levels of NO, NO₂, 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) |
| 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, NO₂, PM₂·₅ and PM₁₀ | Transportation | Reduction in the road and non-road movement | The concentration of NO and NO₂ decreased by approximately 63 and 53% respectively during the lockdown compared to before lockdown. Levels of PM₂·₅ and PM₁₀ decreased 13 and 32%, respectively during the lockdown. | Sicard et al. (2020) |
| Madrid       | 14th to 25th March 2020 | NO₂ | | | The Copernicus Sentinel-5P satellite data showed a significant decline in NO₂ concentration in the city. | Zambrano-Monserrate et al. (2020) |
| Barcelona, Madrid and Seville | March 2019 and 2020 | NO₂ | Transportation | Mobility reduced up to 90% | NO₂ emission decreased by 20–30% in the mentioned cities during the lockdown. | Muhammad et al. (2020) |
| Barcelona    | 16th February to 30th March 2020 | PM₁₀, BC, NO₂ and SO₂ | Industrial activity, harbor emissions, construction works, dust resuspension | Restricted social contact, closing of commercial place and administrative centres, | The concentration of PM₁₀ in air was reduced by 28 to 31% during two-week lockdown period as compared to before lockdown. The BC and NO₂ significantly decreased (by 45 to 51%) during the lockdown period as compared to before lockdown. There was no significant change in the concentration of SO₂. | 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 ($\mu$g 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
| 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) |
| 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)      |
| 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$_3$ levels significantly declined during the lockdown period | Shrestha et al. (2020) |
and 29.3%, respectively. The concentrations of NO, NO₂, CO and PM₁₀ 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, NO₂, 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). PM₁₀ and PM₁₀ 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 NOₓ 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 NO₂ pollution (Archer et al. 2020). Several studies reported decline of various pollutants for this period (Table 7). The concentration of NO₂ declined by 25.5%, with an absolute decrease of 4.8 ppb during the lockdown period (Berman and Ebisu 2020). The concentration of PM₂.₅ also declined during the same period compared to previous years (2017–2019). Another study from New York City recorded decreases in PM₂.₅ and NO₂ 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 NO₂ 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 NO₂ 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 PM₂.₅ 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 NO₂ 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 PM₁₀, NO₂, SO₂, 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 NO₂, 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 PM₁₀, PM₂.₅, NO₂, SO₂, 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 PM₂.₅, NO₂ and CO declined substantially; however, the concentration of O₃ increased by 15% during the lockdown period (Kerimray et al. 2020). Otmani et al. (2020) reported that the concentrations of NO₂, SO₂, and PM₂.₅ 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 NO₂ and CO concentrations significantly declined after the lockdown in Amsterdam, Bogota, Sao Paulo, and San Francisco. The levels of PM₁₀, NO₂, 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 increasing 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.

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