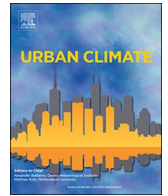




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Impact of lockdown on air quality over major cities across the globe during COVID-19 pandemic

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ABSTRACT

In present study, the variation in concentration of key air pollutants such as $PM_{2.5}$, PM_{10} , NO_2 , SO_2 and O_3 during the pre-lockdown and post-lockdown phase has been investigated. In addition, the monthly concentration of air pollutants in March, April and May of 2020 is also compared with that of 2019 to unfold the effect of restricted emissions under similar meteorological conditions. To evaluate the global impact of COVID-19 on the air quality, ground-based data from 162 monitoring stations from 12 cities across the globe are analysed for the first time. The concentration of $PM_{2.5}$, PM_{10} and NO_2 were reduced by 20–34%, 24–47% and 32–64%, respectively, due to restriction on anthropogenic emission sources during lockdown. However, a lower reduction in SO_2 was observed due to functional power plants. O_3 concentration was found to be increased due to the declined emission of NO. Nevertheless, the achieved improvements were temporary as the pollution level has gone up again in cities where lockdown was lifted. The study might assist the environmentalist, government and policymakers to curb down the air pollution in future by implementing the strategic lockdowns at the pollution hotspots with minimal economic loss.

1. Introduction

The new coronavirus disease 2019 (COVID-19) originated from Wuhan, China, in late December 2019 has now become a serious threat to the entire humankind (Wang et al., 2020; Gautam and Hens, 2020). The novel coronavirus, similar to severe acute respiratory syndrome coronavirus (SARS-CoV) and the Middle East respiratory syndrome coronavirus (MERS-CoV), is found to be zoonotic in nature. Many studies have reported that COVID-19 is an acute respiratory disease that damages the respiratory system and lungs (Huang et al., 2020). The World Health Organization (WHO) has a declared Public Health Emergency of International Concern (PHEIC) on 30th January 2020 (Bherwani et al., 2020a). In February 2020, the COVID-19 outbreak started in India, Spain, Iran and other parts of the world. By the end of March 2020, the epidemic turned into the pandemic. As per statistics, the virus has affected 215 countries with around 30 M confirmed COVID-19 cases and caused 961,400 deaths across the globe, as of 20th September 2020 (WHO, 2020). The virus is spreading at an alarming rate, which shows the exponential growth in the number of confirmed positive cases and deaths. Considering the highly contagious characteristics of the virus and to contain the spread of the

Abbreviations: COVID-19, Coronavirus diseases 2019; SARS-CoV, Severe acute respiratory syndrome coronavirus $\leq 2.5 \mu\text{m}$; MERS-CoV, Middle East respiratory syndrome coronavirus $\leq 10 \mu\text{m}$; $PM_{2.5}$, PM_{10} , Particulate matter with diameters; NO_2 , Nitrogen dioxide; SO_2 , Sulphur dioxide; O_3 , Ozone; BC, Black carbon; CO, Carbon monoxide; AQI, Air Quality Index; WHO, World Health Organization; PHEIC, Public Health Emergency of International Concern

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disease, governments have imposed specific policies to restrict the person-to-person contact in their respective countries (Gautam, 2020a). Various social gathering places such as schools, universities, shopping complexes, cinemas, industrial and business activities are shut, traveling is restricted to contain the spread of the virus (Bherwani et al., 2020b). Moreover, most governments have imposed a complete nationwide lockdown to curb the impact of the virus by completely restricting the movement of people and to attain the social distancing (Muhammad et al., 2020). Such restriction measures are the prime non-pharmaceutical aid to flatten the pandemic curve of COVID-19. Initially, the lockdown was implemented in Wuhan city, China on 23rd January 2020 as a containment strategy, which was followed by other countries (Wang and Su, 2020). After China, Italy was the most affected country where the number of COVID-19 cases reached 6387 on 8th March 2020. Subsequently, Italian government imposed lockdown and other restrictions in different regions in multiple phases, which led to a complete nationwide lockdown in Italy by 23rd March 2020 (Ceylan, 2020). Similarly, India, the second-largest country in terms of the population went into complete lockdown on 25th March 2020 (Kumari and Toshniwal, 2020). Moreover, many cities in US also imposed partial lockdown in the beginning of March, which turned into the complete lockdown as the virus spread exponentially across the country (Muhammad et al., 2020). The lockdown period varies across countries around the world, for example, China lifted the lockdown on 23rd March 2020 while the prolonged lockdown ended on 31st May 2020 with specific rules and restrictions in India. According to a study, around 4 billion people, which makes half of the world population, are observing lockdown to maintain the social distancing (Sandford, 2020). Overall, the lockdown has significantly reduced the various human activities, transportation (air, water, road), factories, industries and other social and economic activities.

The complete lockdown across the globe has affected the global economy and mobility and created chaos among people in many ways. The global outbreak of virus has severely affected the economic growth of entire world (Rajput et al., 2020). According to a report from the International Monetary Fund (IMF), the COVID-19 pandemic would push the global economy into a recession and economy may reduce the growth rate by 4% in 2020 (ABD, 2020). The outcomes of the pandemic will be far worse than the 2009 global financial crisis, which will leave more than 100 million people unemployed by the end of 2020 (ILO, 2020). However, there are studies which suggest that lockdown has dramatically improved the air quality in various regions (Dutheil et al., 2020; Gautam, 2020b).

At the dawn of the 21st century, industrialization and modernization are at its peak across the globe, which is continuously increasing the hazardous levels of air pollution. Air pollution has adverse effects on every being that exists on earth. The primary sources of air pollution are identified as industrial emission, biomass burning, vehicular emission, fuel combustion in power plants, transportation, road dust, coal combustion, garbage burning, etc. In addition, indoor air pollution is also a major concern these days. Indoor air is mainly contaminated by various activities, which uses different appliances such as stoves, smoke, refrigerators, carpet dust, etc. The continuous exposure to highly polluted air has adversely affected the human beings. The poor air quality has become a matter of global concern. According to a report, every year, around 4.2 million people die prematurely due to exposure to poor air quality, which causes lung cancer, heart disease, asthma and other chronic respiratory disorders (Gupta et al., 2020). Moreover, more than 90% of the world's population lives in places where air quality exceeds the standard limits set by WHO (WHO, World Health Organization, 2020). The particulate matter with diameters $\leq 2.5 \mu\text{m}$ ($PM_{2.5}$) and $10 \mu\text{m}$ (PM_{10}), nitrogen dioxide (NO_2), sulphur dioxide (SO_2) and ozone (O_3) are five major pollutants, which provide information about the air quality. The primary source of $PM_{2.5}$ and PM_{10} emission are power generation plants, industries, vehicle engines due to the combustion of solid and liquid fuels (Aggarwal and Toshniwal, 2019). These are the most harmful pollutants that can penetrate the lungs and bloodstreams to cause respiratory diseases, heart attacks and premature deaths. Similarly, long exposure to high concentrations of NO_2 in the air can lead to asthma and respiratory infections. Likewise, prolonged intake of SO_2 and O_3 can cause shortness of breath, lung diseases such as asthma, and chronic bronchitis (Kampa and Castanas, 2008). Along with health, air pollution also shows an adverse impact on the environment, climate, vegetation, economy, etc. The recent outbreak of COVID-19 has reportedly shown a positive impact on the environment. A tremendous reduction in major air pollutants has been observed during the lockdown implemented in the COVID-19 pandemic. This situation can be considered as a great opportunity to understand the primary emission sources at a location. Moreover, this scenario can be used by policymakers and authorities to develop efficient and effective future policies to curb down the pollution levels.

Recently many researchers reported that lockdown measures observed due to COVID-19 pandemic had shown a considerable impact on environment in various countries. For instance, Sharma et al. (2020) reported that air quality has improved due to reduced emission levels of $PM_{2.5}$, PM_{10} , CO and NO_2 in 22 Indian cities during lockdown phase. Similarly, Velásquez and Lara (2020) applied a gaussian approach to determine the probability and correlation between COVID-19 cases and NO_2 concentration in Lima. Sicad et al. (2020) studied the variation in NO_2 and O_3 concentration in four European cities and Wuhan during lockdown period. They reported that air quality was significantly improved while O_3 production was increased in considered cities. Pacheco et al. (2020) reported that air quality in Ecuador was greatly improved during lockdown with a 23% decrement in the NO_2 concentration. Similarly Lokhandwala and Gautam (2020) studied the air quality index of a highly polluted city in India. Pei et al. (2020) observed that the major air pollutants showed a significant reduction in three cities in China, namely Beijing, Wuhan and Guangzhou. Krecl et al. (1987) studied the impact of COVID-19 policy implications in the Mega city of Sao Paulo during lockdown. They reported a significant drop in the NO_x concentration level in the urban areas. Further, Pata (2020) studied the impact of COVID-19 pandemic on environmental pollution in eight different US cities and found that the ongoing pandemic decreased the $PM_{2.5}$ emission in the US. Similarly, Sarfraz et al. (2020) investigated the relationship between COVID-19 and NO_2 concentration level in New York City and revealed that environmental quality significantly improved during the pandemic. Moreover, Agarwal et al. (2020) analysed the influence of lockdown measures on air pollution of six megacities of India and six cities in China and concluded that air pollution in considered cities reduced drastically. Due to strict restrictions on air transportation, air quality in 44 cities of north China has been improved in the initial stage of lockdown (Bao and Zhang, 2020). Table 1 demonstrates several previous studies conducted to analyze the impact of implemented control measures on air quality during lockdown period.

Table 1

Previous studies analyzing the impact of COVID-19 on air quality of different locations. The text in bold represents the contributions of the present study.

| Study | Study location | Pollutants types | Key observations |
|--------------------------------------|---|---|---|
| Zambrano-Monserrate and Ruano (2020) | Quito, Ecuador | $PM_{2.5}$, NO_2 and O_3 | $PM_{2.5}$ and NO_2 concentration decreased while O_3 concentration increased. |
| Collivignarelli et al. (2020) | Milan, Italy | PM_{10} , $PM_{2.5}$, BC, CO benzene, SO_2 and NO_x | All pollutants except SO_2 show a significant reduction. |
| Lian et al. (2020) | Wuhan, China | $PM_{2.5}$, PM_{10} , SO_2 , CO, NO_2 and O_3 | The AQI of Wuhan City decreased significantly, the higher the population density the more significant the decline. |
| Baldasano (2020) | Barcelona and Madrid (Spain) | NO_2 | The NO_2 concentrations in Barcelona and Madrid (Spain) were reduced by % and 62%, respectively. |
| Gautam (2020b) | India, Italy, Spain, France | NO_2 | NO_2 concentration reduced during lockdown period. |
| Adams (2020) | Ontario, Canada | $PM_{2.5}$, NO_2 , NO_x and O_3 | $PM_{2.5}$ concentrations did not change, while a moderate reduction in O_3 concentration was observed. NO_2 and NO_x levels were strongly reduced. |
| Selvam et al. (2020) | Gujarat, India | AQI, $PM_{2.5}$, PM_{10} , SO_2 , CO, NO_2 and O_3 | NO_2 was reduced by 30–84%, while O_3 increased by 16–58%. Overall, AQI improved by 58% as compared to 2019. |
| Kumari and Toshniwal (2020) | Delhi, Mumbai, Singrauli (India) | $PM_{2.5}$, PM_{10} , SO_2 , NO_2 and O_3 | The concentration of PM_{10} , $PM_{2.5}$, NO_2 and SO_2 reduced by 55%, 49%, 60% and 19% and 44%, 37%, 78% and 39% for Delhi and Mumbai, respectively. |
| Pacheco et al. (2020) | Ecuador | NO_2 | NO_2 concentration was reduced by up to 23%. |
| This study | Beijing, Bengaluru, Delhi, Las Vegas, Lima, London, Madrid, Moscow, Mumbai, Rome, Sao Paulo, and Wuhan | $PM_{2.5}$, PM_{10}, SO_2, NO_2 and O_3 | $PM_{2.5}$, PM_{10} and NO_2 reduced significantly during lockdown. However, SO_2 and O_3 showed a mixed trend. Moreover, observed results showed that the achieved air quality improvement is temporary. |

The above-discussed literature suggests that the restriction measures implemented during pandemic have positively impacted the air quality in different countries (as shown in Fig. 1). It can be observed that pandemic has demonstrated a positive impact on air quality of the world's great economic countries, including European countries (such as Spain, Italy and UK), which remains a tourist's attraction throughout the year, countries in the Americas (US, Brazil and Peru), where large production and consumption projects induce high pollution, and Asian countries, including China and India, which are the most populated and highly polluted countries. These are the most affected regions globally, which collectively account for more than 60% COVID-19 cases and deaths. Since the aforementioned countries are adversely affected by the ongoing pandemic, their governments pro-actively implemented effective restriction policies and lockdown measures to contain the spread of the disease. The air quality in these countries is supposed to be highly influenced by the imposed lockdown.

Therefore, the primary objective of the present study is to investigate and quantify the global impact of restriction measures on air quality of several countries that are highly affected by COVID-19 pandemic. The present work has great significance in this ongoing pandemic that how much concentration of major air pollutants reduced during the lockdown. In this study, a comparative analysis of the variation in the air quality of 12 cities from highly COVID-19 affected countries across the globe is presented for the first time. For which, a pre- and post-lockdown comparison in daily concentrations of five key air pollutants, including $PM_{2.5}$, PM_{10} , NO_2 , SO_2 and O_3 , is conducted to investigate the impact of social pause caused by COVID-19 on air quality using ground-based data from 162 monitoring stations. In addition, monthly concentrations of air pollutants during lockdown period of 2020 are compared with the previous year (2019) data to unfold the effect of restricted emissions under similar meteorological conditions. Soon after the lockdown was implemented, many researchers reported a significant decrease in atmospheric pollution. However, no study has been reported yet, that has analysed the air quality after restriction measures were removed. The present study also focuses on the air quality in cities where the lockdown has been lifted.

The uniqueness of the present study is that it reflects the ground truth regarding air quality ($PM_{2.5}$, PM_{10} , NO_2 , SO_2 and O_3) not only during the lockdown but also after the lockdown has been lifted. In addition, it compares the air quality during the lockdown period of the year 2020 to that of the year 2019 to investigate the impact of restriction measures under similar climatic conditions. Moreover, the strength of present work has been amplified because it puts forward a global scenario of air quality by selecting the most affected countries by the COVID-19 pandemic. To the best of our knowledge, no study has been performed to examine the impact of COVID-19 on the environmental pollution on a global scale, so far. The results of this study will help in identifying the specific emission sources of major air pollutants. In addition, it will help the policymakers and scientific research community in devising a sustainable environmental management plan to curb down the high level of air pollution in polluted regions.

2. Methodology

2.1. Site description

The whole world is dealing with the deadly novel coronavirus disease, which has adversely affected the well being, lives, market and economy of the world. However, the air quality is supposed to be improved, as governments have implemented lockdowns to

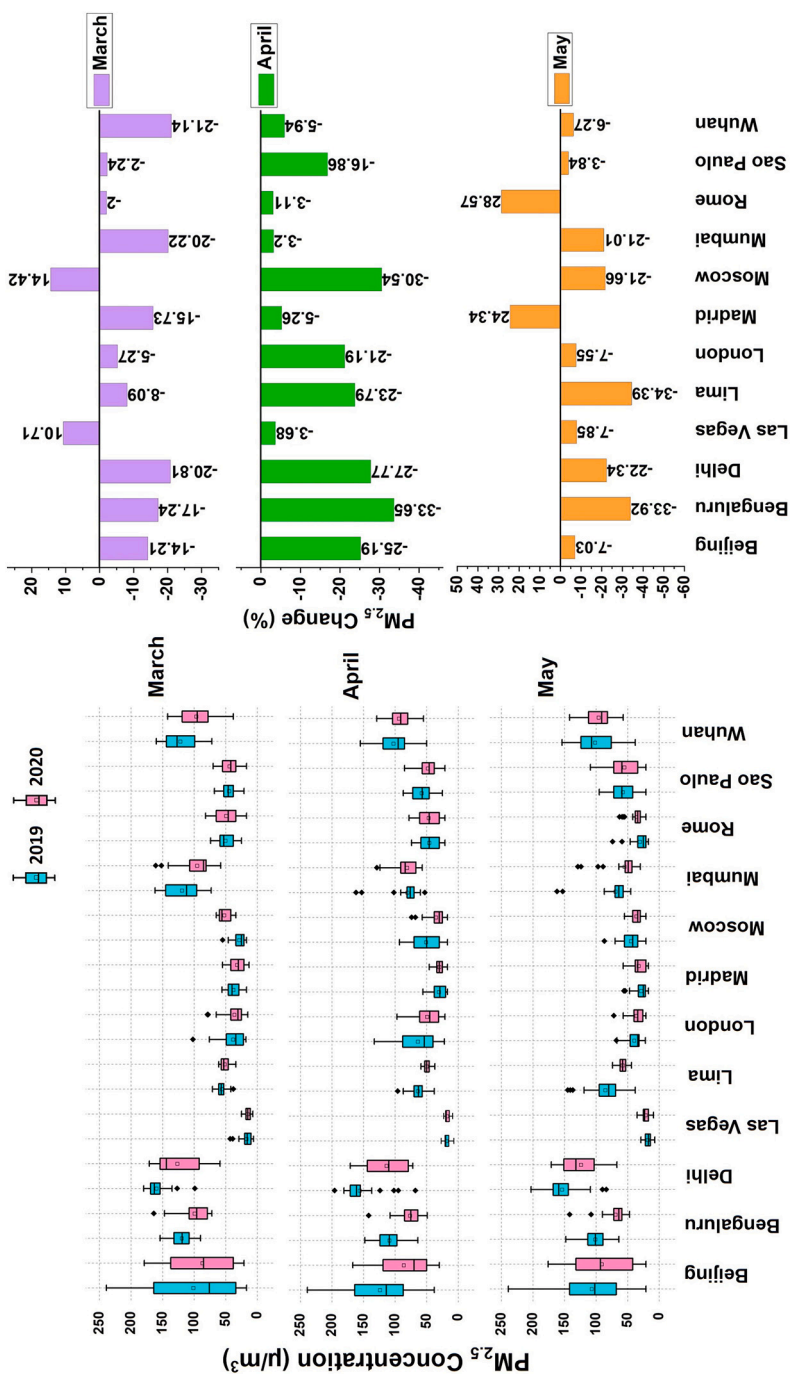


Fig. 1. Schematic representation of impact of lockdown on air quality during COVID-19 pandemic.

Table 2
Selected cities and their lockdown information.

| S.no | City | Country | Region | Station | Lockdown | Unlock |
|------|-----------|---------|---------------------------|---------|------------|------------|
| 1. | Beijing | China | East Asia | 26 | 15/02/2020 | 24/03/2020 |
| 2. | Bengaluru | India | Asia | 5 | 25/03/2020 | 31/05/2020 |
| 3. | Delhi | India | Asia | 14 | 25/03/2020 | 31/05/2020 |
| 4. | Las Vegas | US | North America | 5 | 16/03/2020 | On going |
| 5. | Lima | Peru | Latin America & Caribbean | 11 | 15/03/2020 | On going |
| 6. | London | UK | Europe | 20 | 23/03/2020 | 1/06/2020 |
| 7. | Madrid | Spain | Europe | 4 | 14/03/2020 | On going |
| 8. | Moscow | Russia | Asia | 20 | 30/03/2020 | On going |
| 9. | Mumbai | India | Asia | 12 | 25/03/2020 | 31/05/2020 |
| 10. | Rome | Italy | Europe | 10 | 11/03/2020 | 18/05/2020 |
| 11. | Sao Paulo | Brazil | Latin America & Caribbean | 14 | 18/03/2020 | On going |
| 12. | Wuhan | China | East Asia | 21 | 23/01/2020 | 24/03/2020 |

contain the spread of the virus. Therefore to investigate the global impact of lockdown on air quality during the COVID-19 pandemic, cities from different continents have been selected. In this study, 12 major cities around the world, namely Beijing, Bengaluru, Delhi, Las Vegas, Lima, London, Madrid, Moscow, Mumbai, Rome, Sao Paulo, and Wuhan are selected to analyze the impact of lockdown on air quality. The selected Asian cities, belong to China (Beijing and Wuhan) and India (Bengaluru, Delhi and Mumbai), falls under the list of top most polluted cities in the world. The main cause of pollution in these cities is the high population. However, due to the implemented lockdown, the human movement and outdoor activities have been significantly reduced. Few cities like London, Madrid, Moscow and Rome are the center of tourist attraction throughout the year. The main sources of air pollution in these cities are the air or road traffic, which has been halted due to shutdown of international transportation. Cities like Las Vegas, Delhi, Sao Paulo and Lima are highly industrialised cities with heavy industries, manufacturing sectors and highly polluting enterprises. The main sources of air pollution in these cities are industrial activities, including production, import/export transportation, etc. Such activities have been temporarily closed due to government guidelines during the lockdown. Besides, these cities have entirely different climatic conditions. For example, Beijing has a temperate monsoon, Delhi has semi-arid, Madrid has a mediterranean climate, Las Vegas has a subtropical hot desert climate, etc. These cities belong to those countries which are highly affected by COVID 19, and hence, a complete lockdown was imposed (Worldometer, 2020). To analyze the global effect of restriction measures on air quality, the locations are selected from different continents/regions across the globe, as shown in Table 2. The primary sources of air pollution in these cities are anthropogenic emissions, therefore a significant effect of lockdown on air quality is expected. Based on the above facts, considered cities provide good and diverse area for analyzing the differences in impact of lockdown on air quality of different regions.

2.2. Air pollutants

Generally, the level of air pollution in a region is measured by concentration of five major pollutants: particulate matter with diameter less than $2.5 \mu\text{m}$ and $10 \mu\text{m}$ ($PM_{2.5}$ and PM_{10}), nitrogen dioxide (NO_2), sulphur dioxide (SO_2) and ozone (O_3). The primary sources of $PM_{2.5}$ are emission through combustion of liquid and solid fuels in vehicles, industries, power plants, etc. It can also be produced from chemical reactions of gases such as SO_2 and nitrogen oxides (NO_x) (Singh and Chauhan, 2020). The main emission sources of PM_{10} are dust from landfills, agriculture, construction sites, wildfires, garbage burning, and dust storms. NO_2 mainly gets in the air due to the burning of fuels in vehicles, power plants, tobacco smoke, etc. Similarly, the main sources of formation of SO_2 are the combustion of fuels in power plants and industries. Other activities, such as extraction of metals from ores, volcano eruption, locomotives, ships, food and other commercial manufacturing units, etc. also generate SO_2 . At the same time, O_3 is produced when sunlight falls on few precursor chemical species emitted from primary sources in the presence of air. The presence of the above-mentioned pollutants in the air is the main cause of poor air quality. Therefore, these five pollutants, including $PM_{2.5}$, PM_{10} , NO_2 , SO_2 and O_3 , are analysed to investigate the impact of COVID-19 on air quality of selected cities.

2.3. Data collection

The daily records of air quality data from 162 monitoring stations spread across 12 selected cities are downloaded from the World Air Quality Index portal (WAQI) (www.aqicn.org). The data at WAQI portal is collected by the stations that are managed by government institutions and departments. The retrieved dataset contains 24-h average concentration values of considered parameters (i.e. $PM_{2.5}$, PM_{10} , NO_2 , SO_2 and O_3). The data is collected for 23 weeks from 1st January 2020 to 10th June 2020 for each considered site. In addition, the daily average air quality data of March, April, and May of 2019 was also downloaded to present a comparison. We assume that level of air pollution in March, April, and May of 2019 was considered normal due to usual conditions, while the variation in air pollution level in March, April and May of 2020 is due to the country-specific government steps taken during the pandemic. Therefore, the monthly concentrations of five key pollutants in three months, including March, April, and May of 2019, are compared with March, April, and May of 2020. In addition, the information regarding lockdown and unlock dates are collected from the regional and global reports, as listed in Table 2. It must be noted that lockdown refers to the minimization of vehicular and

human movement, shut down of commercial and industrial activities except for essential services, which lead to a temporary reduction in air pollution.

2.4. Analysis method

Present study follows a comparative approach to analyze the effect of lockdown or restriction measures implemented due to ongoing COVID-19 pandemic on the air quality across the globe. Firstly, the variation in trends of the five key air pollutants has been analysed to investigate a comparison in air quality before and after the lockdown. Additionally, the concentration level of key air pollutants has also been compared during lockdown period and after the lockdown was lifted. Finally, the monthly concentrations of selected air pollutants for the lockdown period (i.e. the month of March, April and May) of 2020 have been compared with the same time frame of 2019. Since the meteorological factors such as temperature, relative humidity, etc., influences air quality. Therefore, the same time frame has been used for comparison to avoid any discrepancies caused by seasonal variations.

3. Results

3.1. $PM_{2.5}$

A notable reduction in $PM_{2.5}$ concentration level was observed in all considered cities (except Las Vegas and Moscow) in March 2020 as compared to March 2019, in all selected cities in April 2020 compared to April 2019, and in 10 cities (except Madrid and Rome) in May 2020 compared to May 2019. A maximum decline in mean concentration of $PM_{2.5}$ in March was noticed in Delhi (−20.8%), Mumbai (−20.2%) and Wuhan (−21.1%). Likewise, in April a maximum decline was observed for Bengaluru (−33.6%), Delhi (−27.7%), Lima (−23.79%), London (−21.1%) and Moscow (−30.5%) whereas Bengaluru (−33.9%), Delhi (−22.3%), Lima (34.3%), Moscow (−21.6%) and Mumbai (−21%) has shown maximum decline in $PM_{2.5}$ concentration levels in May (Fig. 2).

The concentration of $PM_{2.5}$ in Las Vegas and Moscow was increased in March 2020, which significantly reduced in April and May due to the lockdown (started in mid- March and April in the United States and Russia, respectively). As the lockdown in Rome lifted in May (18th May 2020), Rome has shown an increment in $PM_{2.5}$ concentration levels during May. Likewise, percentage change in $PM_{2.5}$ concentration in Wuhan was low in April and May as compared to March as the lockdown in Wuhan was lifted in the last week of March (24th March 2020). In contrast, the $PM_{2.5}$ concentration has been increased in Mumbai and Madrid during April and May, respectively. This increment may be ascribed to the relaxation given by their governments for essential movements.

In regards to daily $PM_{2.5}$ concentration from 1st January 2020 to 10th June 2020, 10 cities including Beijing, Bengaluru, Delhi, Las Vegas, Lima, Madrid, Mumbai, Rome and Wuhan have shown significant decrement in $PM_{2.5}$ concentration accounting the lockdown implementation date (Fig. 3). It must be noted that Beijing, Bengaluru, Delhi, Lima, Mumbai and Wuhan are highly polluted cities where anthropogenic activities are the primary source of emission. They have shown a sharp decline in $PM_{2.5}$ concentration during the lockdown period. On the contrary, Las Vegas, London, Madrid and Sao Paulo have low air pollution, i.e., their $PM_{2.5}$ concentration level is quite low as compared to heavily polluted cities due to which variation in low polluted cities was not much evident in lockdown period.

3.2. PM_{10}

All cities, except Moscow and Sao Paulo, have shown a significant decline in PM_{10} concentration in March 2020 as compared to March 2019. In April, all cities have shown a great reduction in 2020 as compared to 2019. However, only seven cities showed a decline in PM_{10} concentrations in May 2020. The maximum reduction in monthly mean concentration of PM_{10} in March was seen in Beijing (−26.5%), Delhi (−27.6%), Lima (−38.7%), Madrid (−27.2%) and Wuhan (−26.8%). Maximum reduction in April was observed in Beijing (−23.7%), Bengaluru (−40.2%), Delhi (−47.3%) and Lima (−45.9%). Maximum declines were observed in Bengaluru (−26.1%), Delhi (−42%), Lima (−29.8%) and Mumbai (−23.3%) in May (Fig. 4).

The daily time series of PM_{10} from 1st January to 10th June 2020, showed that PM_{10} concentrations significantly reduced in 8 cities including Beijing, Bengaluru, Delhi, Lima, Madrid, Mumbai, Rome and Wuhan while in London and Moscow, PM_{10} concentration was high in initial days of lockdown which gradually decreased (Fig. 5).

3.3. NO_2

NO_2 is one of the major air pollutants which generally has high concentrations at all locations irrespective of their regions. A significant reduction in NO_2 concentration was observed in all cities except Las Vegas and Moscow in March 2020 compared to March 2019. It is because the lockdown in Las Vegas and Moscow was implemented in the March-end and April-beginning, respectively. However, all considered cities have shown a high reduction in NO_2 concentration in April and May 2020 as compared to 2019. Maximum reduction in NO_2 concentration was observed in Beijing (−34.5% in March, −32.6% in April, −34.7% in May), Bengaluru (−36.8% in March, −56.4% in April, −30.7 in May), Delhi (−31.6% in March, −64.5% in April, −54.2% in May), Lima (−48.5% in March, −61.66% in April, −59.9% in May), Madrid (−33.1% in March, −51.3% in April and −39.4% in May) and Rome (−31.6% in March, −43.5% in April, −33% in May) (Fig. 6).

In addition, all cities except Lima have shown a significant reduction in daily NO_2 concentration after the lockdown was implemented. Lima has shown a mixed trend where NO_2 concentration declined in initial days of lockdown, which further increased. It

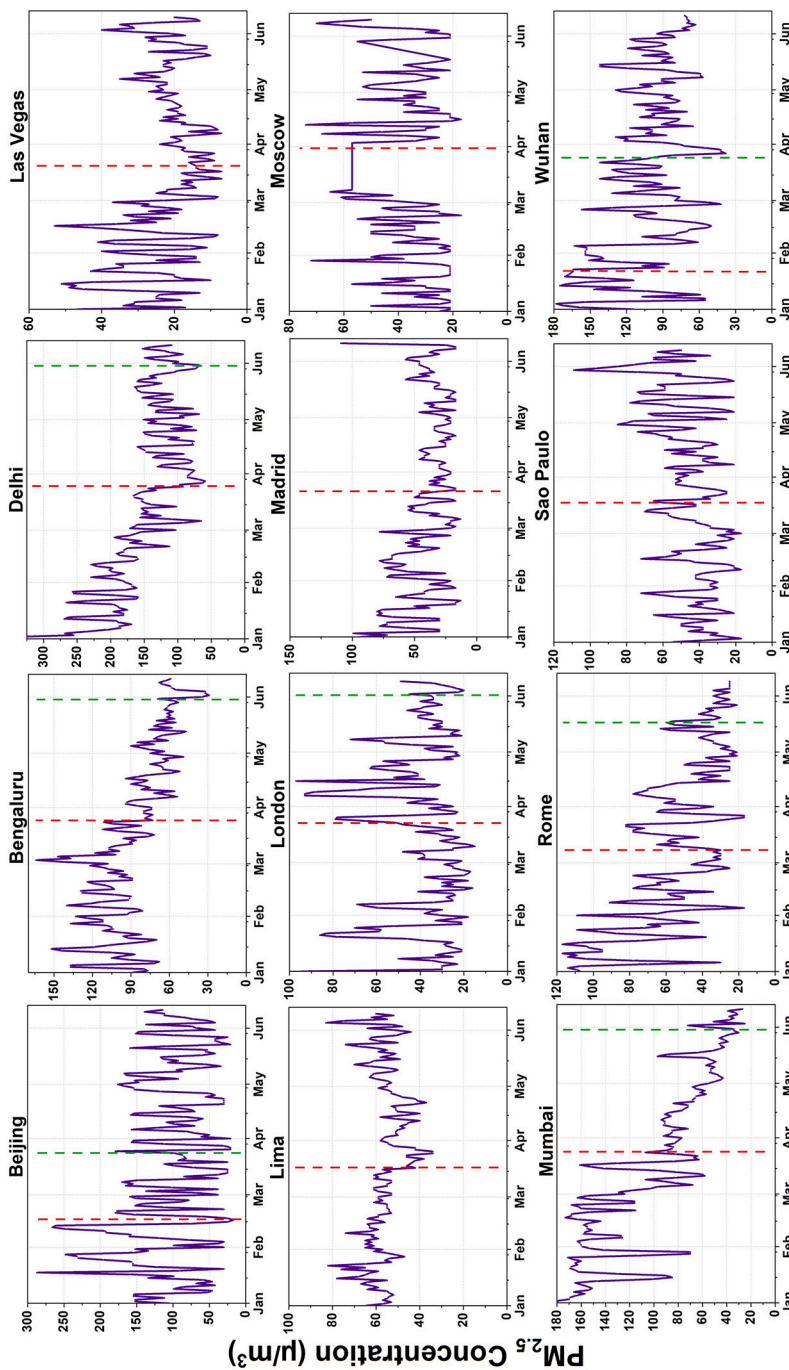


Fig. 2. The box plots of $PM_{2.5}$ concentration in 12 cities for March, April and May of 2019 and 2020 (left) and percentage change in $PM_{2.5}$ concentration in March, April and May of 2020 as compared to 2019 (right).

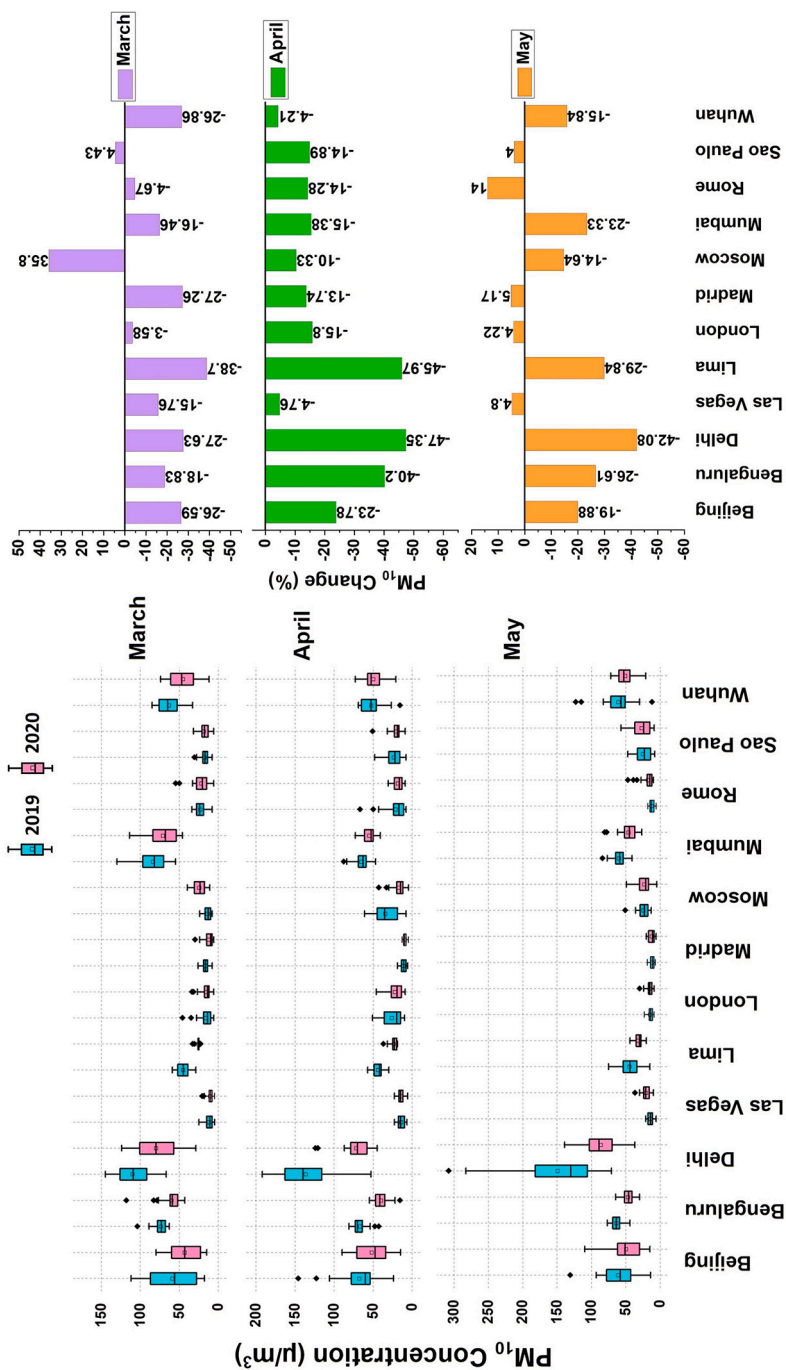


Fig. 3. Daily $PM_{2.5}$ concentration from 1st January 2020 to 10th June 2020 for 12 cities. Lockdown started (red line) and lockdown lifted (green line). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

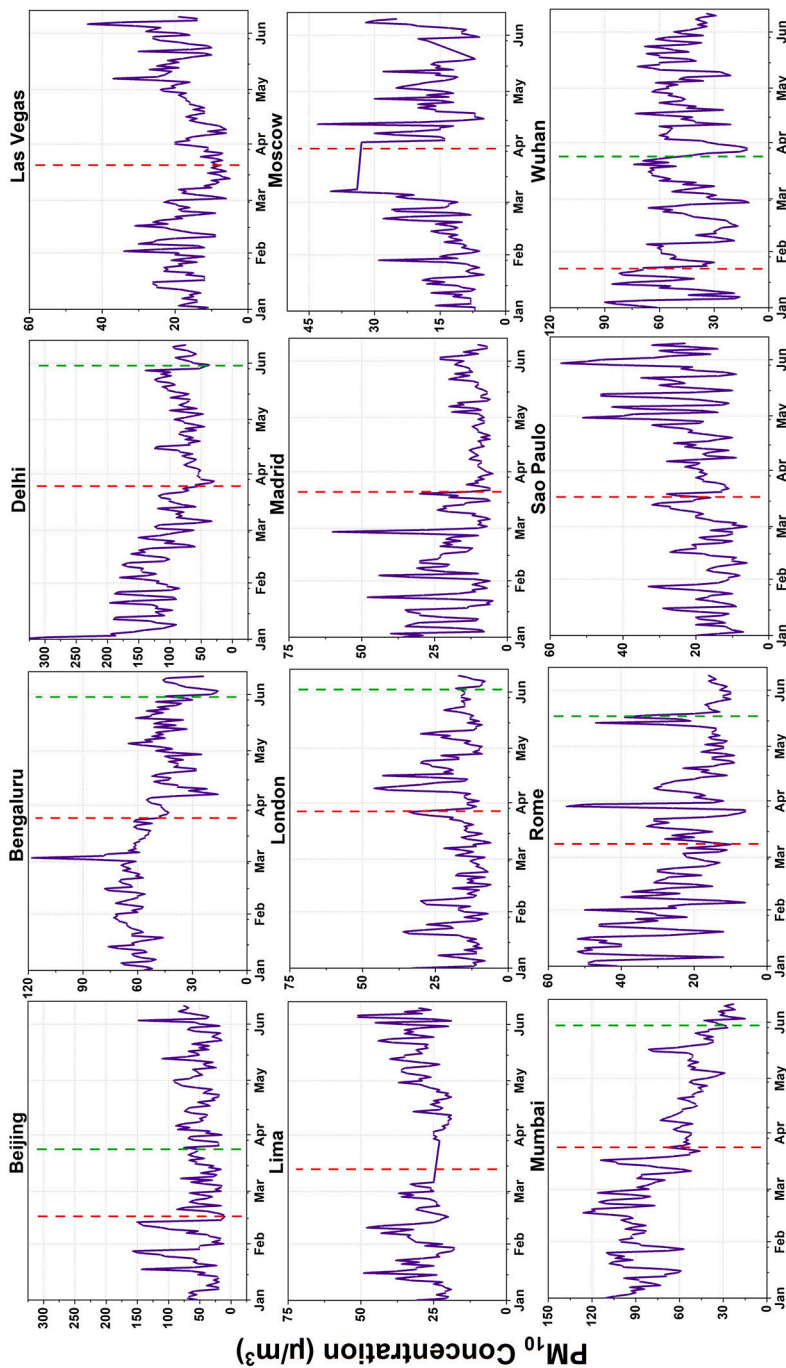


Fig. 4. The box plots of PM_{10} concentration in 12 cities for March, April and May of 2019 and 2020 (left) and percentage change in PM_{10} concentration in March, April and May of 2020 as compared to 2019 (right).

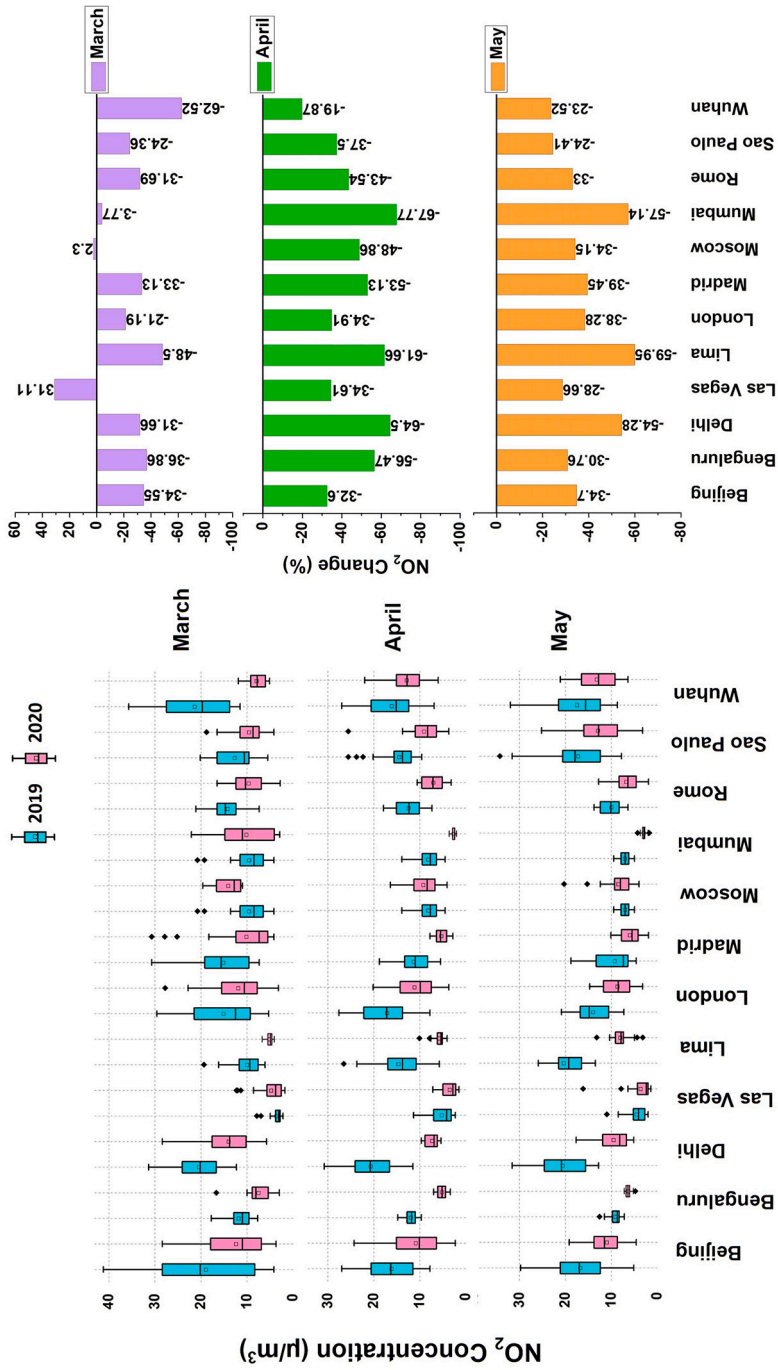


Fig. 5. Daily PM_{10} concentration from 1st January 2020 to 10th June 2020 for 12 cities. Lockdown started (red line). For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

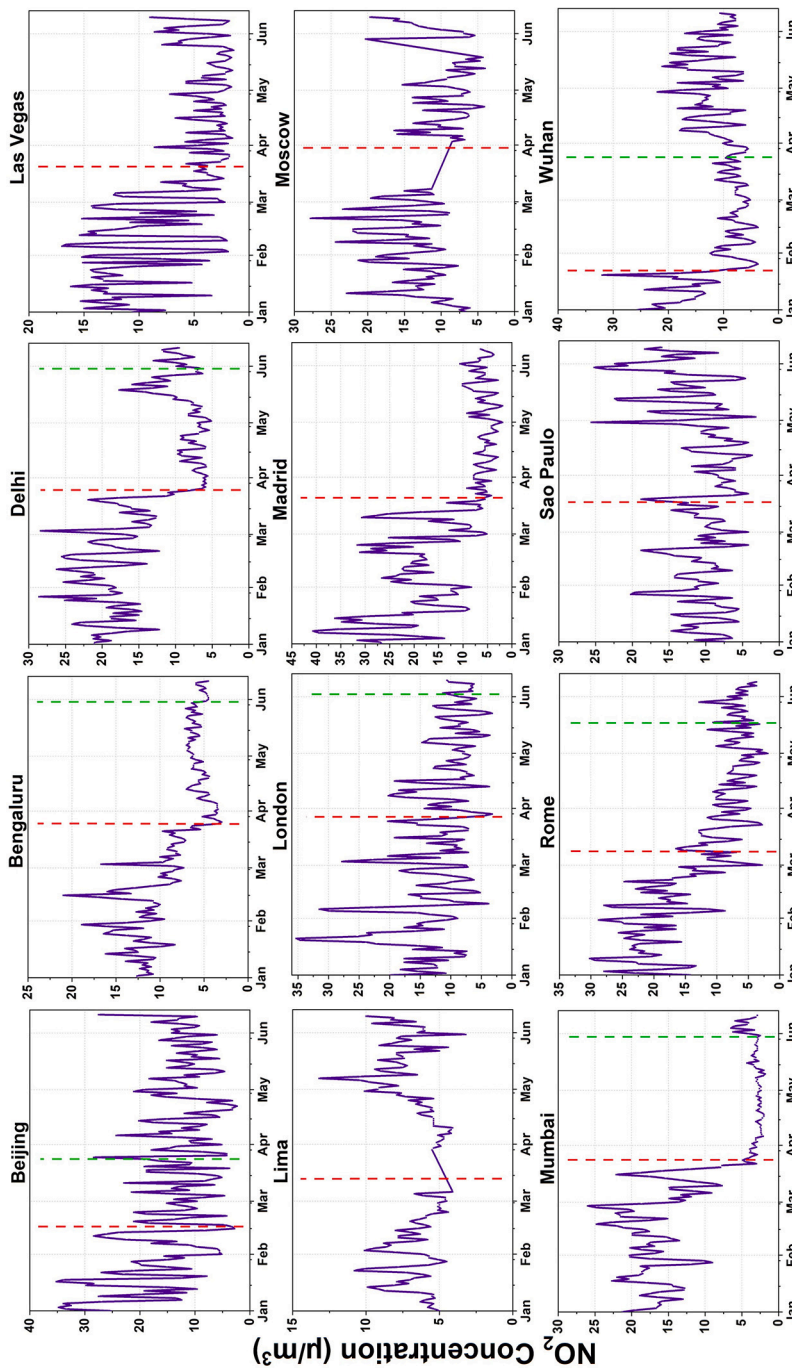


Fig. 6. The box plots of NO₂ concentration in 12 cities for March, April and May of 2019 and 2020 (left) and percentage change in NO₂ concentration in March, April and May of 2020 as compared to 2019 (right).

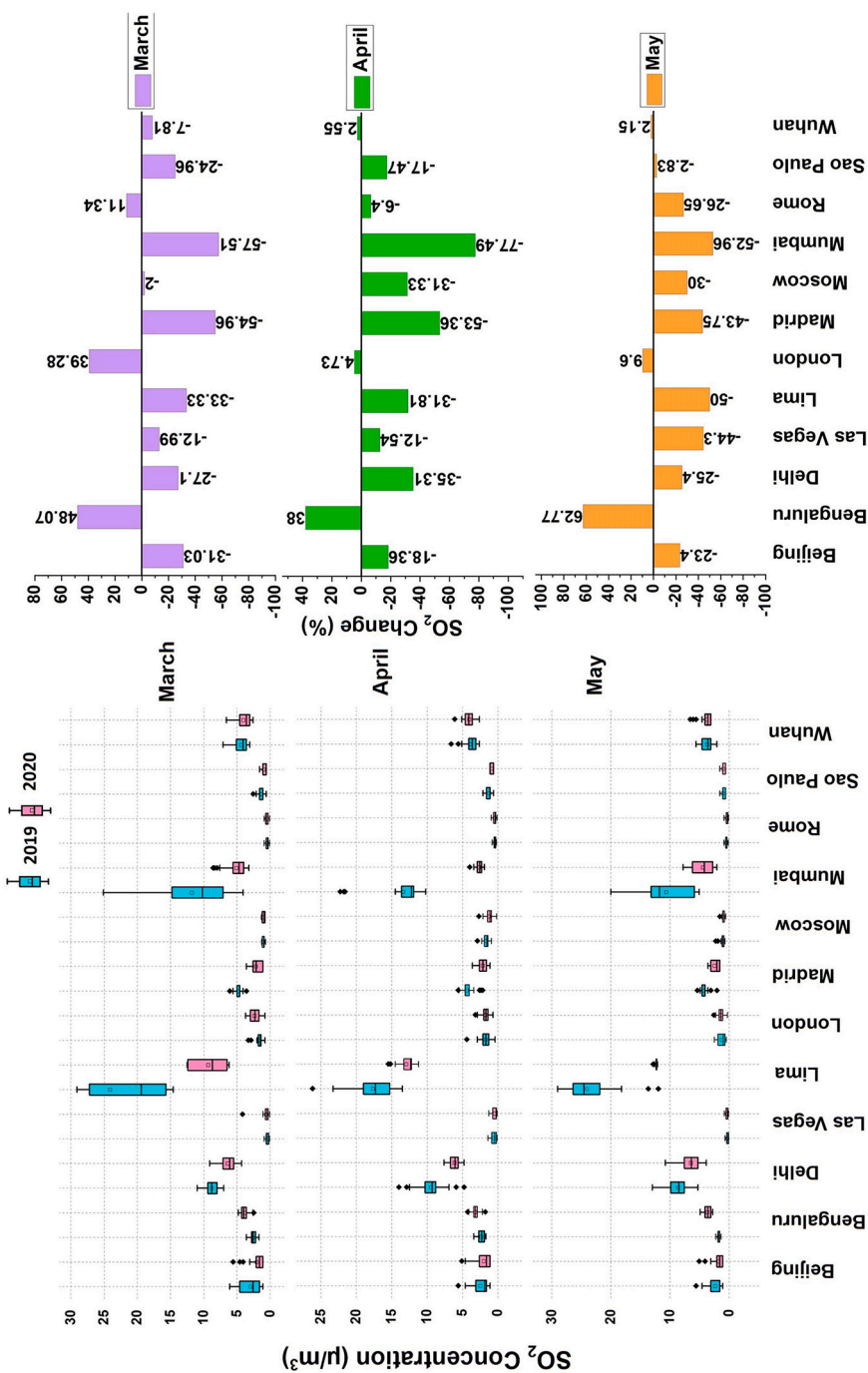


Fig. 7. Daily NO₂ concentration from 1st January 2020 to 10th June 2020 for 12 cities. Lockdown started (red line). Lockdown lifted (green line). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

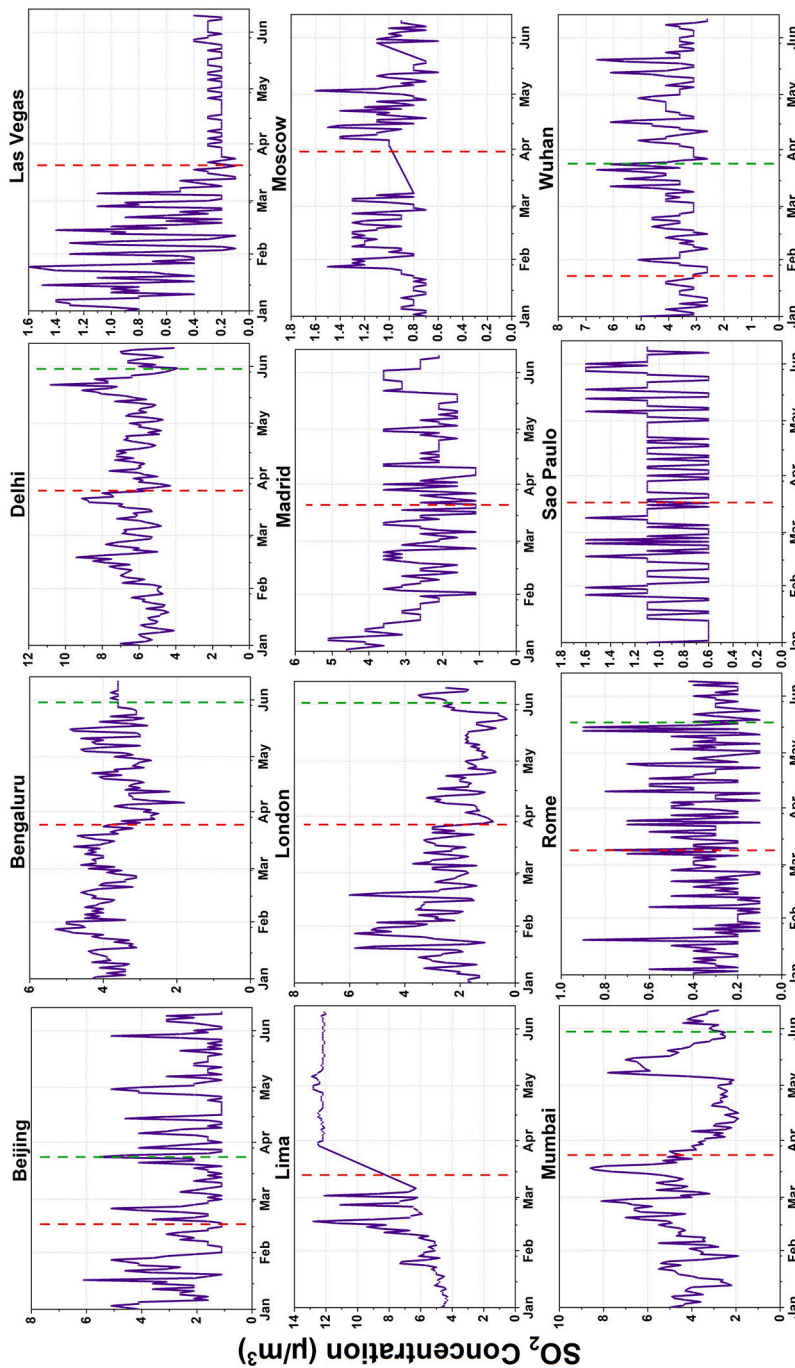


Fig. 8. The box plots of SO₂ concentration in 12 cities for March, April and May of 2019 and 2020 (left) and percentage change in SO₂ concentration in March, April and May of 2020 as compared to 2019 (right).

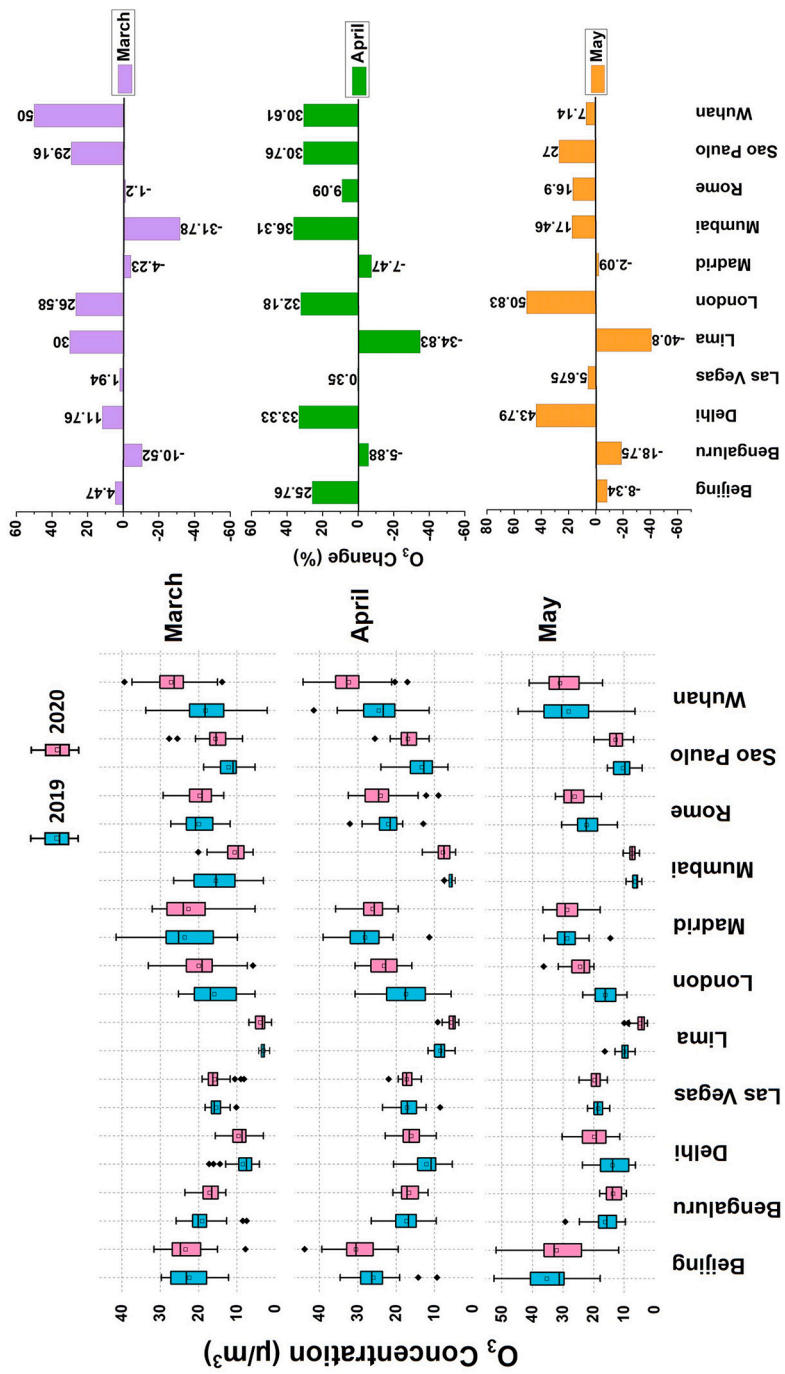


Fig. 9. Daily SO₂ concentration from 1st January 2020 to 10th June 2020 for 12 cities. Lockdown started (red line) and lockdown lifted (green line). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

can also be observed that Wuhan has shown a remarkable drop in NO_2 concentrations during lockdown while a significant increase is noticed as the lockdown was lifted (Fig. 7).

3.4. SO_2

The comparison between monthly data of SO_2 concentration in 2019 and 2020 shows a mixed trend (Fig. 8). Eight cities in March, nine cities in April and eight cities in May have shown a reduction in SO_2 concentration 2020 as compared to 2019. Maximum reduction was observed in Mumbai (−57.5%) followed by Madrid (−54.9%), Lima (−33.3%) and Beijing (−31%) in March 2020. In April, the maximum decline was seen in Mumbai (−77.4%), followed by Madrid (−53.3%) and Delhi (−35.3%). Similarly in May 2020, Mumbai (−52.9%) followed by Lima (−50%), Las Vegas (−44.3%) and Madrid (−43.7%) showed maximum reduction SO_2 concentration as compared to May 2019. On the contrary, three cities (Bengaluru, London, Rome) in March 2020, 3 cities (Bengaluru, London, Wuhan) in April and May 2020 showed a higher SO_2 concentration. It must be noted that Lima followed by Mumbai and Delhi, are high SO_2 cities as compared to other selected cities (Fig. 8).

The daily concentration of SO_2 in selected cities didn't show any regular trend during lockdown period: SO_2 concentration during lockdown declined in 5 cities (Beijing, Bengaluru, Delhi, Las Vegas and London) while increased in 3 cities (Lima, Rome and Wuhan) (Fig. 9).

3.5. O_3

On comparing the available data of 11 cities, a mixed trend across cities was observed for monthly mean O_3 concentrations: seven cities in March 2020, eight cities in April 2020 and seven cities in May 2020 saw higher O_3 concentration as compared to 2019. On the contrary, four cities (Bengaluru, Madrid, Mumbai, Rome) in March 2020, 3 cities (Bengaluru, Lima, Madrid) in April 2020 and four cities (Beijing, Bengaluru, Lima, Madrid) in May 2020 had higher O_3 concentrations. Mumbai (−31.7%) followed by Delhi (−10.52%) showed maximum decline in March 2020 while Lima (−34.8% in April, −40.8% in May) followed by Bengaluru (−5.8% in April, −18.7% in May) and Madrid (−7.4% in April, −2% in May) showed maximum reduction in O_3 concentrations. On the other hand, Delhi (+33.3% in April, +43.7% in May), London (+26.5% in March, +32.1% in April, +50.8% in May), Sao Paulo (+29.1% in March, +30.7% in April, +27% in May) and Wuhan (+50% in March, +30.6% in April) has shown maximum increase (Fig. 10).

In regards to the daily concentration of O_3 , mixed trends were observed during lockdown phase: 3 cities (Bengaluru, Mumbai and Sao Paulo) showed a decline while seven cities (Beijing, Delhi, Las Vegas, Madrid, Moscow, Rome and Wuhan) showed a sharp increment in daily O_3 concentrations in lockdown period (Fig. 11).

4. Discussion

Too much exposure to poor air quality may harm the humans and ecosystem beyond expectations. Air pollution has become a serious and global topic of concern. COVID-19 has presented an opportunity to study the emission sources of several air pollutants and different ways in which their concentration can be reduced. The air quality of cities considered in present study has been analysed under the influence of COVID-19 lockdown. The selected locations are greatly affected by the COVID-19 pandemic, which accounts for more than 60% of the total COVID-19 cases and deaths worldwide (Worldometer, 2020). These countries have implemented strict lockdown to stop the spread of the disease, leading to a significant reduction in air pollution levels in selected cities. The above discussed results demonstrate that the concentration of particulate matters ($PM_{2.5}$ and PM_{10}) and NO_2 have significantly reduced in March, April and May of 2020 compared to the same period of 2019. This reduction is observed for all selected cities, except Las Vegas, Moscow and Rome. The main reason for this discrepancy is the timings of lockdown implementation. In few cities, the lockdown was imposed in late March, due to which these cities might have kept the monthly mean values prior to lockdown, which resulted in an overall high concentration of pollutants in March 2020. Moreover, in few cities such as Beijing, Delhi, London, Rome and Wuhan, the lockdown was lifted in April or May due to which things turned back to normal as people started traveling, industrial and business activities, etc. restarted following the government issued guideline. This might be the reason that these cities have shown higher or comparable monthly mean concentrations in 2020 as compared to 2019. Further, a detailed trend analysis is carried out to represent the variation in daily concentration of these air pollutants. The daily $PM_{2.5}$, PM_{10} and NO_2 concentrations showed a significant decline after the enforcement of lockdown. The primary reason for the reduction in their concentrations is the halt on anthropogenic activities such as transportation, traveling, industrial activities, which are the primary source of such pollutants (Sharma et al., 2020).

According to the discussed results, SO_2 and O_3 have shown a mixed trends (i.e., SO_2 and O_3 concentrations reduced for some cities while remained unchanged for some cities) in March, April and May of 2020 as compared to the same period of 2019. The primary reasons for the observed mixed trends of SO_2 are following. First, the major emission sources of SO_2 are coal-based power plants that might have been operational at many places during the lockdown, due to which SO_2 concentrations did not reduce in some cities (Kumari and Toshniwal, 2020). Second, the seasonal forest fires and sand storms in few regions have influenced the level of these pollutants in few cities (Sicard et al., 2020). Third, the local meteorological conditions such as temperature, rainfall, wind speed, solar radiation, etc. are few factors that highly affect the SO_2 concentration levels (Lokhandwala and Gautam, 2020). Due to these reasons, the SO_2 concentration remained steady or increased for a few cities like Lima, Madrid, Moscow, Rome, Sao Paulo and Wuhan, during lockdown. Moreover, there is no evident reduction in SO_2 concentration in 2020 as compared to 2019 for these locations.

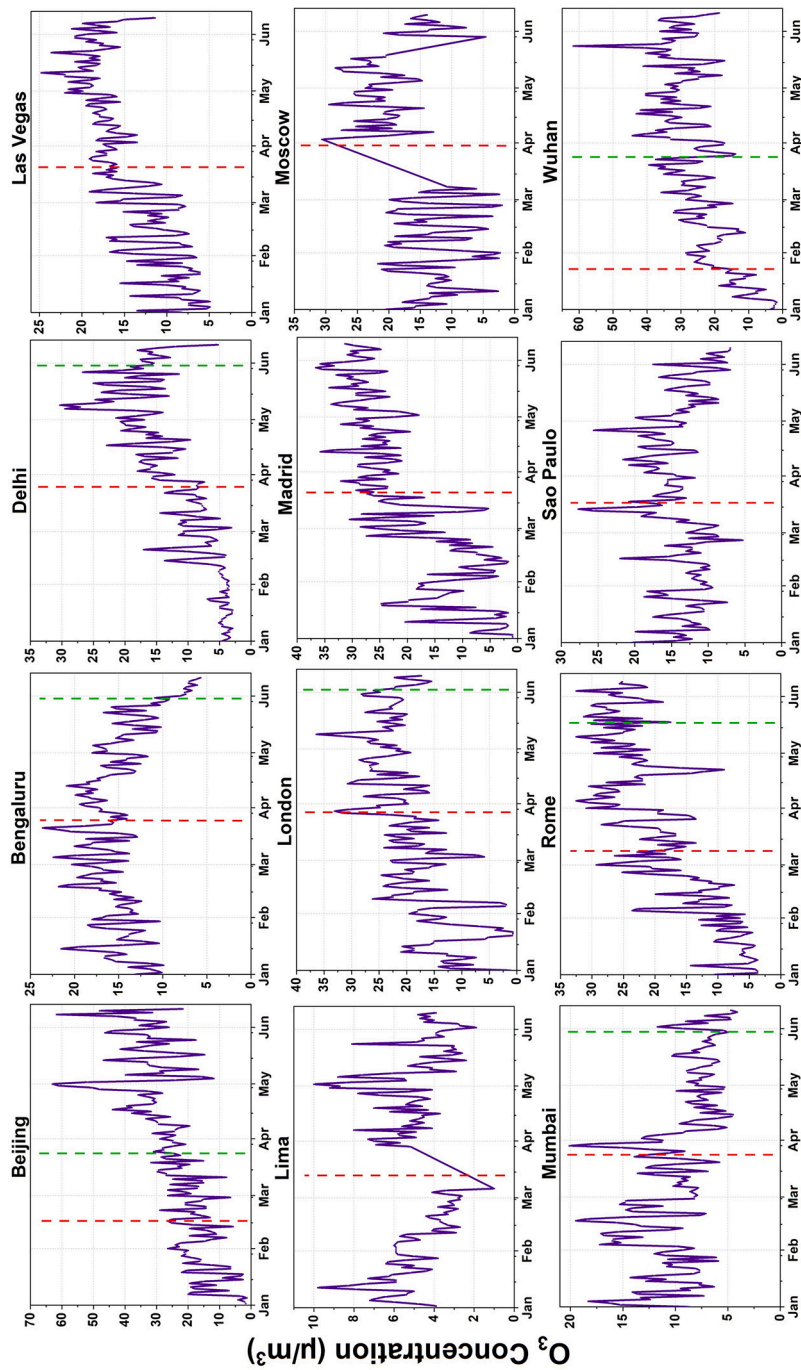


Fig. 10. The box plots of O₃ concentration in 12 cities for March, April and May of 2019 and 2020 (left) and percentage change in O₃ concentration in March, April and May of 2020 as compared to 2019 (right).

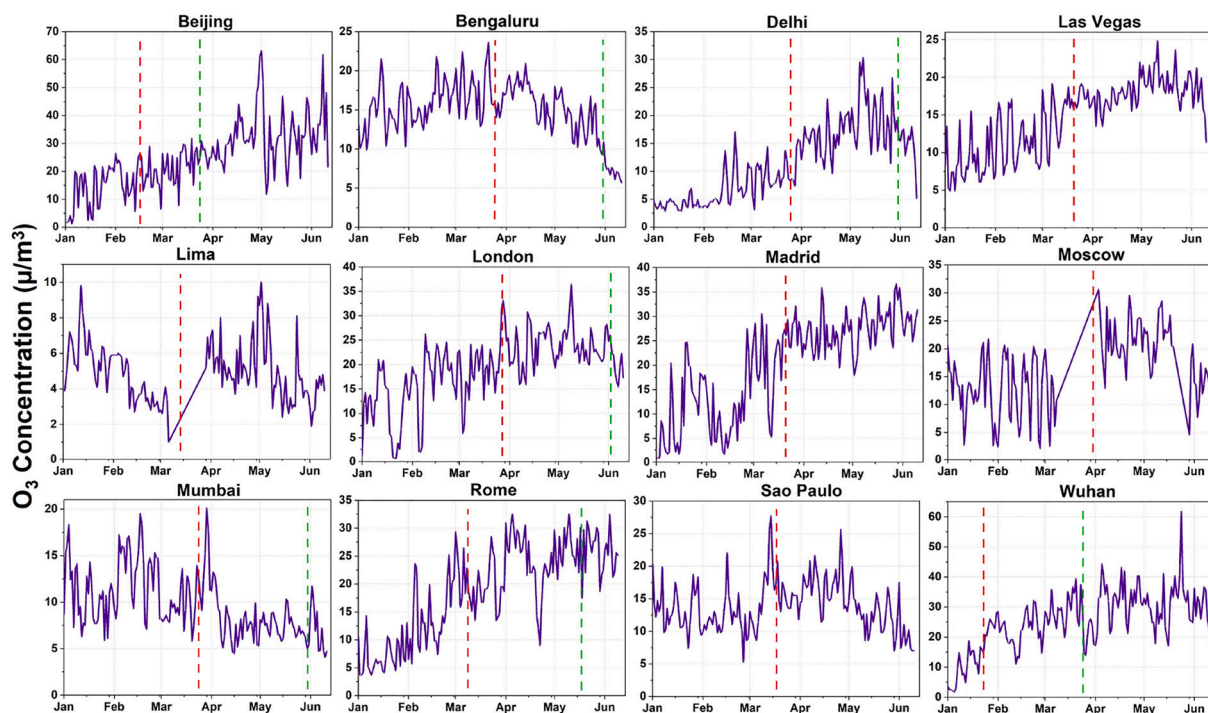


Fig. 11. Daily O_3 concentration from 1st January 2020 to 10th June 2020 for 12 cities. Lockdown started (red line) and lockdown lifted (green line). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

Similarly, the O_3 has shown a discrepancy of irregular trends as O_3 concentration is increased in most of the cities, like Beijing, Delhi, Las Vegas, Lima, London, Madrid, Moscow, Rome, Sao Paulo and Wuhan, while reduced in Bengaluru and Mumbai, during lockdown period. The increment of O_3 concentration level can be witnessed for the following reasons. Firstly, O_3 is a secondary pollutant, which depends on the local availability of its precursors (i.e., NO_x and volatile organic compounds (VOCs)). The reduction in emission of its precursors has increased the O_3 concentration in the atmosphere. Secondly, the nitrogen oxide (NO) consumes O_3 under the titration process: $NO + O_3 = NO_2 + O_2$. However, the O_3 consumption by NO has been reduced due to a decrement in NO concentration during lockdown compared to pre-lockdown period, subsequently, the amount of O_3 in the atmosphere has been increased. Thirdly, the local meteorology (e.g., sunlight, temperature, etc.) also impacts the construction and destruction of O_3 . For example, the minimum and maximum temperature in May 2020 has been comparatively higher than that of March 2020 (Kumari and Toshniwal, 2020). However, the O_3 concentration decreased in cities like Bengaluru and Mumbai for the following reasons: In these cities, the temperature remained constant, specifically low during these months, due to which O_3 concentrations couldn't increase. Moreover, Bengaluru and Mumbai have witnessed heavy rains during the considered time frame. Generally, O_3 production is limited during cool or rainy weather conditions (Kwak et al., 2017).

The performed analysis also shows that the concentration level of pollutants such as $PM_{2.5}$ and PM_{10} , NO_2 , SO_2 and O_3 has increased after the lockdown is lifted. It can be observed from the above-mentioned results that in Beijing, Bengaluru, Delhi, Mumbai, Rome and Wuhan, the concentration level of considered pollutants substantially go up once the lockdown is revoked in these cities. This observation leads to an important finding that the air quality improvement achieved during lockdown is very short-term and temporary.

Overall, in European cities, including London, Madrid and Rome, the major sources of pollution are residential buildings, small scale industrial and commercial activities which might have continued in the lockdown period. Therefore, pollutants in these cities have not shown much reduction in lockdown phase. However, in highly polluted cities like Beijing, Bengaluru, Delhi, Lima, Mumbai, Rome and Wuhan, the impact of lockdown on pollution reduction is highly observable as the primary emission sources of pollution in these cities are anthropogenic activities, which drastically reduced in lockdown phase. Based on the studied ground-level station data, it can be concluded that three major air pollutants $PM_{2.5}$, PM_{10} and NO_2 are highly reduced across the world due to the concurrent implementation of lockdown in the ongoing COVID-19 pandemic.

5. Conclusion and future work

The COVID-19 pandemic has emerged as a serious threat to the entire humankind in many ways. However, the pandemic triggered restriction measurements and the lockdown has come out to be a “blessing in disguise” as the earth is reviving itself. This study investigates the impact of lockdown, which was imposed as a precautionary measure to control the spread of COVID-19, on the air

quality of different cities across the globe. To conduct the investigation, the ground-based station air pollution data from 162 monitoring station in 12 cities from the countries which are highly affected by COVID-19 has been analysed. The variation in concentration of five key air pollutants, including $PM_{2.5}$ and PM_{10} , NO_2 , SO_2 and O_3 , has been studied. In addition, the monthly average concentration of these pollutants during March, April and May of 2020 is compared with the same time frame of 2019. The significant findings of the study are as follows:

- The major pollutants, including $PM_{2.5}$, PM_{10} and NO_2 , have shown a remarkable reduction in post-lockdown period compared to pre-lockdown period, for all selected locations due to restricted emissions during the lockdown phase. Similarly, the concentration level of these pollutants has been highly reduced in March, April and May of 2020 compared to those of 2019.
- The highly polluted cities like Beijing, Bengaluru, Delhi, Lima, Mumbai, Rome and Wuhan have witnessed a notable decline in air pollution in the lockdown period of 2020 compared to the same time of 2019. The $PM_{2.5}$ concentration levels showed a drop in the range of 20.2% to 34.3%. Similarly, PM_{10} concentration was reduced by 23.7% to 47.3%. However, a higher decline, between 31.6% and 64.5%, has been observed in the case of NO_2 .
- SO_2 concentration level showed a mixed trend during the lockdown phase. For few cities like Lima, Madrid, Moscow, Rome, Sao Paulo and Wuhan, SO_2 concentration remained unchanged in lockdown phase as the main emission source of SO_2 is power plants, which remained operational at most of the location. O_3 concentration level demonstrated an increment in the lockdown phase at many locations, which might be due to the reduction of O_3 consumption in the titration process and change in meteorological conditions over time.
- Notably, the observed variations and improvements in air quality are temporary as the concentration level of studied pollutants has gone up again in cities where lockdown was lifted.

To sum up, the findings of this study suggest that the lockdown has led to a significant reduction in air pollution across the globe, irrespective of the geographical and climatic condition of the considered locations. Although the present environmental changes are temporary, this short-lived enhancement in air quality during lockdown may be an encouraging signal for governing authorities and policymakers to achieve better air quality through planned and strict restrictions on emission sources. The governments may implement a strategic lockdown at the pollution hotspots for a period of time to control the pollution levels in their regions with minimal economic loss.

However, present work has certain limitations that can be worked upon in future studies. Firstly, the variation of remaining parameters such as carbon monoxide, benzene, black carbon and air quality index can be studied in further research. Secondly, this study is conducted for 12 cities that are highly affected by COVID-19; future studies can incorporate a larger number of locations irrespective of the number of COVID-19 cases. Thirdly, a more detailed analysis of variation in O_3 concentration levels can be carried out to understand the mixed trend.

Declaration of Competing Interest

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

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