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The Impact of the COVID-19 Lockdown on Climate

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Abstract: The Earth is a dynamic planet, permanently influenced by societal and environmental interactions. On December 31, 2019, the outbreak of COVID-19 was reported in Wuhan, China. With the prevalence of the COVID-19 pandemic, lockdown measures were implemented in many cities. Some studies reported significant reductions in emissions from local transportation, industrial production, power generation, and a variety of other economic activities have improved air quality and visibility in many cities, and this improvement has been attributed to reduced activity. The aim of the current study is to evaluate the impact of the COVID-19 pandemic on weather changes during the lockdown period. Numerous studies that have examined the relationship between climate change and restrictive measures have shown a significant reduction in ambient air pollutants in the urban environment. In general, the concentrations of PM_{10}, $PM_{2.5}$, CO, NO_2, O_3, and SO_2 were reduced while O_3 concentration increased. Also, the land surface temperature level has decreased in some areas, which has been negligible and requires long-term follow-up. Although continued lockdown can temporarily improve air quality and reduce air temperature, it is not a solution to improve the air quality that kills millions annually, and appropriate policies should be adopted to improve the weather conditions.

Keywords: COVID-19, Weather, Climate, Lockdown

1. Introduction

The Earth is a planet that is changing in a dynamic way, permanently shaped through social-ecological interactions. In dynamic and nonlinear systems like our planet, variations and changes are usual, but crossing certain thresholds can bring the stability of the system to a new state, which will have a significant impact on different temporal and spatial scales [1-3]. One of the challenges our society faces is understanding and anticipating early the effects of such changes on all sciences such as economics, social sciences, or medicine [3].

The main resources of the earth make human life possible and no one can survive without them. All living things on earth need air, food, water and, sunlight every day to continue to grow. It is inconceivable to live without these essential needs. Therefore, it is very important to store and use them properly [4]. In recent years, one of the key factors that has become the subject of much scientific research is the effect of weather change on human health and its implications over time [5]. In many developing countries, economic growth has exacerbated emissions of air pollutants, with severe environmental and human health consequences. Air quality levels for more than 80 people living in cities with air pollution are below WHO standards (WHO 2020) [6].

Today, technologies are being developed globally in a rapid way for human progress. Hence, the world must accept the challenges that remain uncertain and unpredictable [4]. In the twenty-first century, the international community is facing a new challenge named coronavirus disease (COVID-19) [7, 8]. Coronavirus disease is a respiratory disease caused by a virus belonging to the coronavirus family. On December 31, 2019, the outbreak of COVID-19 was reported in Wuhan, China. The nature of the easy and rapid spread of COVID-19 has threatened the world [9, 10]. According to the global database until 7 August 2021, the total number of cases infected and deaths from COVID-19 worldwide reached more than 200 million and more than 4 million respectively, according to the global database [11]. Although, between 2000 and 2019, six major pandemic and epidemic outbreaks swept our planet, namely the Middle East respiratory syndrome (2012–2020), the Zika fever (2015–2016), the West-African Ebola virus epidemic (2013–2016), Avian influenza (2008–2014), H1N1 influenza (2009), and Severe

Acute Respiratory Syndrome (SARS) (2002–2004). However, none of these achieved the widespread impacts and the spatial extent that the COVID-19 did [3].

Due to the rapid emergence of COVID-19, particularly government lockdown measures aimed at containment, economic activity related to transportation and movement has almost completely halted in many countries [12, 13]. As a precautionary measure, most countries have taken various measures to control the spread of COVID-19, such as closing schools and universities, not allowing public transportation, closing non-essential commercial advertisements, and prohibiting mass gatherings. As COVID-19 is a communicable disease, social distancing needs to be maintained and people are encouraged to stay home [13, 14].

Although lockdown has severely reduced economic, industrial, and social activities, it temporarily improves air quality in most polluted cities around the world due to the massive reduction in energy consumption, especially fossil fuel combustion. For example, observing reductions in greenhouse gas emissions such as sulfur dioxide (SO_2), carbon dioxide (CO_2), and nitrogen dioxide (NO_2) was observed, and during February and March 2020, CO_2 emissions were reduced by 18% in China. Also, due to the lockdown policy, including traffic restrictions and people staying at home, public transport has been reduced by 90% [15-18]. For example, passenger vehicle traffic reduced by 40% in the USA. Lockdown measures have reduced noise and improved urban air quality. For instance, the return of cars to roadways compensates 50 to 70% of the air quality improvements gained during quarantine [15, 17, 19, 20]. Although most air pollutants have been reduced during containment, some pollutants have increased, such as ozone (O_3). Some studies have also confirmed that the reduction in air pollution levels is short-term [21, 22]. Also, the increase in air pollution concentrations in the cities has elevated the temperature on both the surface and the atmosphere, resulting in urban climate change. Hence, lockdown due to air pollution reduction has also reduced the air temperature [20]. However, these transient environmental benefits can be utilized to activate new social and environmental policies as an important beneficial impact as well as a learning model for governments [23].

Activities are expected to undergo major changes, and predicting the impact of the pandemic on different sectors has very important social benefits. Our review of the current epidemiology of weather change caused by COVID-19 has identified a number of important gaps. Few studies have evaluated the impact of the COVID-19 pandemic on weather and air quality, and most studies have examined the impact of weather on COVID-19 transmission and mortality cases. However, to the best of our knowledge, the impact of the COVID-19 pandemic on weather change has not been investigated in a systematic review. Also, in this systematic review study, unlike others, studies that have used the machine learning technique have been analyzed. All of the following analyses are required to evaluate the socio-ecological and socio-economic changes in all cities throughout the world and to demonstrate the positive consequences in order to reap some benefits from the global crisis. The aim of the current study is to evaluate the impact of the COVID-19 pandemic on weather changes during the lockdown period.

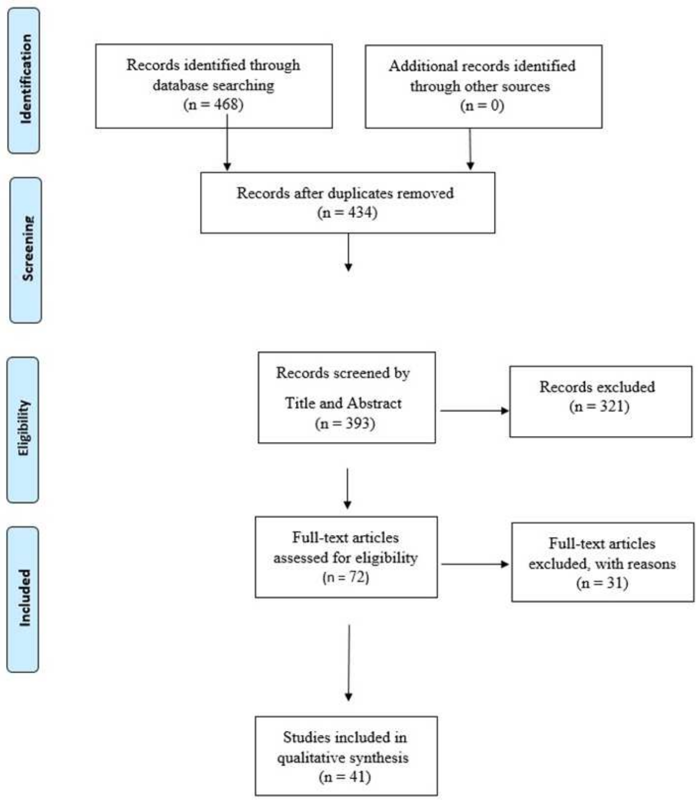

Figure 1. *PRISMA Flow Diagram of identification, screening and inclusion of studies.*

2. Method

We have conducted a systematic review of the literature concerning the impact of the COVID-19 pandemic on weather change. The research was performed in compliance with the PRISMA criteria, Preferred Reporting Items for Systematic Reviews and Meta-Analyses, and the Flow Diagram is shown in Figure 1. The research was conducted between January 2020 and August 7th, 2021 in PubMed database. It was used the Advanced Search Builder and the keywords were searched in [Title OR Abstract]. We have filtered only research articles published in English language and selected the following keywords: ("Weather" OR "Climate" OR "Air quality") AND ("COVID-19" OR "SARS-COV-2") AND "Lockdown."

Any relevant studies were included after scanning the references in previously published review articles. We obtained a total of 40 eligible published research articles in their final version and one paper in its preprint version. For some of them, we chose to include only the main findings that clearly fit the purpose of this review.

3. Air Quality and COVID-19

Air pollutants can have a significant impact on human health. The main environmental cause of various diseases and premature deaths worldwide is exposure to air pollution. According to the World Health Organization, 7 million people die each year from diseases and illnesses that are directly associated with poor air quality [6]. A significant increase in the prevalence of respiratory disorders, such as asthma, pneumonia, chronic obstructive pulmonary disease (COPD) and other diseases has been linked to air pollution in recent years [24]. Generally, five major air pollutants including particulate matter ($PM_{2.5}$ and PM_{10}), ground-level ozone (O_3), carbon monoxide (CO), nitrogen dioxide (NO_2), and sulfur dioxide (SO_2) are regulating the air quality in the environment [25]. Prior to the onset of the COVID-19 pandemic, with an increase in $PM_{2.5}$ between 2016 and 2018, nearly 10,000 additional premature deaths occurred in the United States. In 2016, these deaths, in addition to their tragedy, also caused $89 billion in economic damage [26]. Long-term exposure to PM with a diameter of less than 2.5 and O_3 is expected to cause about 8.8 million fatalities per year [27]. Each year, NO_2 causes 4 million new instances of pediatric asthma [28].

Studies indicate that the relationship between coronavirus and air pollution is unclear, as evidenced by both positive and negative correlations [29-31]. Recent research suggests that exposure to greater levels of air pollutants, such as O_3, SO_2, CO, NO_2, PM_{10}, and $PM_{2.5}$, increases the risk of COVID-19 infection. Also, various studies show that both short-term and long-term air pollution exposures are related with a broad variety of poor health outcomes, including higher fatalities, increased hospital admissions, and higher outpatient visits [32, 33]. Many studies have shown that COVID-19 mortality is increased by air pollution, although COVID-19 lockdown could decrease air pollution levels at the same time [34-37].

With the prevalence of the COVID-19 pandemic, lockdown measures were implemented in many cities. Some studies reported significant reductions in emissions from local transportation, industrial production, power generation, and a variety of other economic activities have improved air quality and visibility in many cities, and this improvement has been attributed to reduced activity [16, 38-42]. For instance, the closure of transportation networks and factories, which are the main emitters of greenhouse gases in the United States, resulted in a 5–10% reduction in air pollutants, including CO_2 [16]. Also, following the lockdown in Wuhan, NO_2 concentrations in China's heavy industrial zones dropped by 40% [38]. In the reviewed articles, changes in air pollutants are shown in Table 1.

Table 1. *Previous studies assessing the air quality effects of COVID-19 at various areas.*

Study	Study location	Pollutants types	Outcome
Baldasano [62]	Madrid and Barcelona (Spain)	NO_2	The levels of NO2 in Madrid and Barcelona (Spain) were reduced by 62% and 50%, respectively.
Broomandi et al. [59]	Tehran, Iran	PM_{10}, $PM_{2.5}$, CO, NO_2, O_3, and SO_2	PM_{10}, SO_2, CO and NO_2 concentrations were reduced significantly during lockdown, while the concentration of O_3 and $PM_{2.5}$ increased.
Jephcote et al. [56]	United Kingdom	NO_2, $PM_{2.5}$, and O_3	The concentrations of NO_2 and $PM_{2.5}$ were reduced while O_3 concentration increased.
Lian et al. [93]	Wuhan, China	NO_2, $PM_{2.5}$, and O_3	The concentrations of NO_2 and $PM_{2.5}$ were reduced while O_3 concentration increased.
Nakada and Urban [65]	Sao Paulo, Brazil	NO, NO_2, and CO	NO, NO_2, and CO concentrations decreased by more than 77.3%, 54.3% and 64.8%, respectively.
Mahato et al. [12]	India	PM_{10}, $PM_{2.5}$, CO, NO_2, NH_3, O_3, and SO_2	There is a substantial reduction in all pollutants except O_3.
Adams [94]	Ontario, Canada	NO_x, NO_2, O_3, and $PM_{2.5}$	NO_2 and NO_x concentrations were significantly reduced. A moderate decrease in O_3 concentration was observed, while the $PM_{2.5}$ concentration did not change.
Nigam et al. [95]	Ankleshwar, Vapi, and Gujarat (India)	PM_{10}, $PM_{2.5}$, CO, NO_2, O_3, and SO_2	There is a substantial reduction in all pollutants except O_3
Zangari et al. [96]	New York, United States	$PM_{2.5}$ and NO_2	$PM_{2.5}$ and NO_2 concentrations decreased 36% and 51%, respectively.

Study	Study location	Pollutants types	Outcome
Collivignarelli et al. [97]	Milan, Italy	NO*, SO_2, BC*, CO, $PM_{2.5}$, and PM_{10}	There is a substantial reduction in all pollutants except SO_2.
Mostafa et al. [98]	Egypt	NO_2, CO, O_3	NO_2 and CO concentrations decreased during the lockdown period, while O_3 concentration increased by at least 4%.
Suman et al. [99]	Delhi, Mumbai, Kolkata, and Chennai (India)	PM_{10} and $PM_{2.5}$	The levels of PM_{10} and $PM_{2.5}$ decreased during the lockdown.
Gautam [100]	Spain, India, France, Italy	NO_2	NO_2 concentration decreased during lockdown period.
Kaviani Rad et al. [75]	Tehran, Iran	PM_{10}, $PM_{2.5}$, NO_2, O_3, and SO_2	The concentrations of NO_2, CO, $PM_{2.5}$, and PM_{10} decreased by 15%, 11%, 6%, and 10%, respectively. However, the O3 and SO2 concentrations increased by 12% and 15%, respectively.
Kumari and Toshniwal [101]	Singrauli, Delhi, Mumbai (India)	PM_{10}, $PM_{2.5}$, NO_2, O_3, and SO_2	The concentrations of NO_2, PM_{10}, SO_2, and $PM_{2.5}$ reduced by 78%, 44%, 39% and 37% and 60%, 55%, 19% and 49% for Mumbai and Delhi, respectively.
Kumari and Toshniwal [57]	Wuhan, Sao Paulo, Rome, Moscow, Madrid, Mumbai, Lima, London, Las Vegas, Delhi, Beijing, and Bengaluru	PM_{10}, $PM_{2.5}$, NO_2, O_3, and SO_2	NO_2, PM_{10}, and $PM_{2.5}$ reduced strongly during lockdown. However, O_3 and SO_2 showed a mixed trend. Furthermore, the observed results revealed that the air quality increase was temporary.
MJ Ju et al. [102]	Korea	PM_{10}, $PM_{2.5}$, CO, NO_2	The levels of NO_2, $PM_{2.5}$, PM_{10}, and CO decreased by 20.41%, 45.45%, 35.56%, and 17.33%, respectively.
Liu et al. [14]	597 major cities worldwide	PM_{10}, $PM_{2.5}$, NO_2, O_3, and SO_2	NO_2 decreased rapidly, followed by PM_{10}, SO_2, $PM_{2.5}$ and CO, but O_3 increased compared to the pre-locking period.
Pacheco et al. [103]	Ecuador	NO_2	The concentration of NO_2 was drop by up to 23%.
Wu et al. [104]	Shanghai, China	PM_{10}, $PM_{2.5}$, CO, NO_2, O_3, and SO_2	The complete lockdown control measures resulted in the highest reduction in NO_2, CO, $PM_{2.5}$, PM_{10}, and SO_2 by 17.9%–50.3% at non-roadside stations and 33.7%–47.7% at roadside stations.
Lovric et al. [70]	Graz, Austria	PM_{10}, NO_2, and O_3	The concentrations of O_3, NO_2, PM_{10} decreased by 11.6-33.8%, 36.9-41.6%, 6.6-14.2%, respectively.
Selvam et al. [105]	Gujarat, India	PM_{10}, $PM_{2.5}$, CO, NO_2, O_3, and SO_2	The concentrations of NO_2, PM_{10}, $PM_{2.5}$, and CO were reduced by 30–84%, 32–80%, 38–78%, and 3–55%, respectively. However, O_3 increased by 16–58%.
Hu et al. [85]	Beijing, China	PM_{10}, $PM_{2.5}$, CO, NO_2, O_3, and SO_2	There is a substantial reduction in all pollutants except O_3.
Masum and Pal [105]	Bangladesh	PM_{10}, $PM_{2.5}$, CO, NO_2, and SO_2	During the lockdown, except NO_2, all other pollutants showed a significant decreasing trend.
Zambrano-Monserrate et al. [106]	Quito, Ecuador	NO_2, $PM_{2.5}$, and O_3	NO_2 and $PM_{2.5}$ concentrations were reduced while O_3 concentration increased.
Sicard et al. [74]	Southern European cities (Nice, Rome, Valencia and Turin) and Wuhan (China)	PM_{10}, $PM_{2.5}$, NO_2, O_3	During the lockdown, except O_3, all other pollutants showed a significant decreasing trend.
Rodriguez-Urrego et al. [50]	50 cities in the world	$PM_{2.5}$	The $PM_{2.5}$ concentration decreased by an average of 12%.
Cole et al. [107]	Wuhan, China	PM_{10}, CO, NO_2, and SO_2	NO_2 and PM_{10} concentrations were reduced during the lockdown, while no significant change was observed in SO_2 and CO levels.
Fu et al. [108]	20 major cities in the world	PM_{10}, $PM_{2.5}$, CO, NO_2, O_3, and SO_2	There is a substantial reduction in all pollutants except O_3.
Shi et al. [109]	Beijing, Wuhan, Milan, Rome, Madrid, London, Paris, Berlin, New York, Los Angeles, and Dehli	$PM_{2.5}$, NO_2, and O_3	NO_2 concentration significantly decreased, while O_3 concentration increased by 2-30%. $PM_{2.5}$ concentrations decreased in all cities except London and Paris.
Zhang et al. [110]	Shanghai, China	PM_{10}, $PM_{2.5}$, NO_2, O_3, and SO_2	During the lockdown, except O_3, all other pollutants showed a significant decreasing trend.
Hashim et al. [111]	Baghdad, Iraq	PM_{10}, $PM_{2.5}$, NO_2, and O_3	The concentrations of PM_{10}, $PM_{2.5}$, and NO_2 decreased, while O_3 concentration increased.
Donzelli et al. [58]	Florence, Pisa, and Lucca (Italy)	PM_{10}, $PM_{2.5}$, NO_2, and O_3	PM_{10}, $PM_{2.5}$, NO_2 concentrations were reduced during the lockdown, while no significant change was observed in O_3 level.
Bassani et al. [68]	Rome, Italy	NO_2	NO_2 concentration were decreased by 43% and 17% in urban and rural sites, respectively.
Otmani et al. [64]	Salé City, Morocco	PM_{10}, NO_2, and SO_2	NO_2, SO_2, and PM_{10} concentrations decreased 96%, 49% and 75%, respectively.
Chen et al. [53]	United States	PM_{10}, $PM_{2.5}$, NO_2, O_3, and CO	During the lockdown, except O_3, all other pollutants showed a significant decreasing trend.
Donzelli et al. [69]	Valencia, Spain	PM_{10}, $PM_{2.5}$, CO, NO_2, NO_x, NO, O_3, and SO_2	Concentrations of all ambient air pollutants decreased.
Bedi et al. [78]	Delhi, Kolkata, Mumbai, and Chennai (India)	PM_{10}, $PM_{2.5}$, NO_2, and O_3	Concentrations of PM_{10}, $PM_{2.5}$, and NO_2 decreased by almost 50% while the concentration of O_3 increased significantly.

4. Global PM Concentration During COVID-19 Pandemic

The term particulate matter is used to describe a complex mixture of solid particles and liquid droplets found in the air. PM is not a single pollutant, but rather a complex and dynamic mixture of composite particles with chemical and biological origins. The most common constituents of PM are primarily ammonia, sulfites, nitrates, black carbon, sodium chloride, mineral dust, and water [43, 44]. Particulates are typically classified into two types depending on aerodynamic diameter: PM_{10} (inhalable particles with a diameter of micrometers and smaller) and $PM_{2.5}$ (fine inhalable particles with a diameter of 2.5 micrometers and smaller) [45]. Exposure to $PM_{2.5}$ causes relatively serious health issues, like non-fatal heart attacks, cardiovascular irregularities, reduced pulmonary function, increased asthma and premature death. PM in the air can be caused by pollutants emitted from factories, vehicles, cultivated areas, burning fossil fuels, construction sites, and asphalt roads [46, 47]. Traffic, industrial activities, domestic fuel burning, nonspecific human-made sources, and dust contribute 15%, 20%, 22%, and 18%, respectively, to urban air pollution caused by $PM_{2.5}$. Numerous research compared PM_{10} and $PM_{2.5}$ concentrations during regular mobility and lockdown periods [48]. Due to the COVID-19 pandemic, PM emission has been reduced in most countries [49-53]. In a study by Myllyvirta, the greatest reduction in PM emissions was in Portugal (55%), followed by Norway (32%), Sweden (30%), and Poland (28%), respectively. Also, in this study, a decrease in PM concentration in Finland, Poland, and Spain was recorded by 16%, 17%, and 19%, respectively. However, no change in PM levels was observed in Croatia and Romania, and PM emissions increased by about 3% in Hungary and Switzerland [54]. One study evaluated changes in $PM_{2.5}$ concentrations in 50 of the most polluted cities in the world. The concentrations of air pollutants were determined using data obtained from air quality monitoring stations operated by local environmental agencies. Overall, $PM_{2.5}$ levels in these cities have dropped by an average of 12%. Only a 5% reduction has been recorded in the European cities in which we generally have higher air quality in normal periods. Also among the surveyed cities, the highest decrease was observed in Bogota (57%) [55]. In a UK study, data from 129 monitoring stations showed that $PM_{2.5}$ and NO_2 levels fell by 16.5% and 38.3%, respectively. This is because traffic levels have been reported to have decreased by 69% [56]. In a study conducted by Kumari et al., they used data from 162 monitoring stations in 12 cities to analyze the monthly concentrations of air pollutants in March, April and May 2020 compared to 2019. In this study, the concentrations of PM_{10} and $PM_{2.5}$ decreased by 24-47% and 20-34%, respectively. In March, the highest decrease in $PM_{2.5}$ emissions was recorded in Delhi, followed by April and May in Bengaluru. $PM_{2.5}$ levels in Moscow and Las Vegas increased in March 2020, but considerably decreased in April and May as a result of the lockdown. Also, the concentration of PM_{10} in all cities in March 2020 was significantly reduced compared with March 2019, except for Moscow and Sao Paulo [57]. In a similar article, Habibi et al reported that in March and April 2020 compared to 2019, the highest decrease in $PM_{2.5}$ was in Sydney, Australia (34.5%). To some extent, these reductions were in line with those in Berlin-Germany (−35.5% in April), Wuhan-China (31% in January), and Perth-Australia (25.5%) [22].

Since the impact of transportation and industrial activities on air quality has been proven. Another study evaluated the impact of mobility restriction policies imposed during the COVID-19 outbreak on air quality levels in three Italian cities: Lucca, Pisa, and Florence. For these purposes, the researchers also made use of meteorological data on temperature, wind speed, rainfall, solar irradiance, and relative humidity for the COVID-19 lockdown period, as well as the same period of the previous years. Meteorological parameters play an important role in determining the concentration of air pollution, especially the PM concentration decreases with an increase in temperature, wind speed, and precipitation rate. However, in this study, no direct evidence of a relationship was observed between the lockdown measures imposed by the Italian government and the reduction of PM in urban centers, except in areas with heavy traffic [58]. This finding is consistent with the above-mentioned study, which found that decreases in $PM_{2.5}$ levels in a European country are significantly lower than in more severely polluted areas of the world. In a study that evaluated the air quality in different regions of Tehran, Iran during the coronavirus pandemic, it was observed that the PM_{10} concentration decreased from 1.4% to 30% but the $PM_{2.5}$ concentration increased from 2% to 50% [59].

However, a study by Gope et al. on air quality changes in 10 of the most polluted cities in the world during the COVID-19 pandemic found that $PM_{2.5}$ concentrations decreased in all cities except Rome [4]. In addition, the study of Dantas et al. revealed an increase in the PM_{10} concentrations in the city of Rio de Janeiro, Brazil during the lockdown period [60]. In general, most studies on ambient air quality have shown a decrease in PM concentrations.

5. Global NO_2 Concentration During COVID-19 Pandemic

Nitrogen dioxide (NO_2) is an air pollutant that is harmful to human health due to the formation of brown photochemical smog. NO_2 is a short-lived climate pollutant, and its atmospheric concentrations can be used to estimate economic activity [44]. Variations in NO_2 levels are influenced by changes in meteorological conditions. Many factors influence the residence period and distribution of gas in the atmosphere, including sunshine hours, fluctuations in daily wind speed and temperature [44, 61]. The primary sources of nitrogen dioxide produced by human activities are industry, power generation, and traffic. Short-term exposure to high NO_2 concentrations can cause respiratory symptoms including bronchitis, coughing, flu, wheezing, and more, as well as aggravate respiratory disorders like asthma [62]. According to the WHO, if the concentration of this gas is more than 200 $\mu g/m^3$, it can cause inflammation in the respiratory tract and eventually lead to asthma [6]. However, its primary disadvantage is that it contributes to the production of two of the most dangerous air pollutants, O_3 and particulate matter [63]. Several studies have shown that nitrogen dioxide concentrations are lower during the lockdown period as compared to the years or months preceding the lockdown, which could be due to the factories closure and limited transportation [57, 62, 64]. NO_2 concentrations are generally reduced significantly more than PM concentrations, sometimes by more than 50% [65]. In a study by Mousazadeh et al., the reduction in NO_2 concentrations was 20-30% in France, Italy, Spain, and China, 40-50% in India, and 30% in the United States [18].

Estimates from the Sentinel-5P satellite of ESA reveal that NO_2 levels were lowered by up to 40 percent during late January to early February 2020 across large cities and industrial areas in numerous Asian and European countries in comparison with similar dates in 2019 [66]. Broomandi et al. reported that the decrease in NO_2 levels in different parts of Tehran was between 1 to 33% with spatial changes [59]. As a result of the coronavirus outbreak, financial activity around the world has slowed, and it is not unexpected that emissions related to transportation and energy have decreased [18]. In a study of 12 cities by Pratima Kumari et al., they found that NO_2 levels dropped in all cities except Moscow and Las Vegas. This is due to the fact that the lockdowns in Moscow and Las Vegas were enacted at the beginning of April and the end of March, respectively. In this study, the highest reduction in NO_2 concentration was in Beijing (34.7% in May), Bengaluru (56.4% in April), Delhi (64.5% in April), Lima (61.66% in April), Madrid (51.3% in April), and Rome (43.5% in April). After the lockdown, all cities except Lima demonstrated a considerable reduction in daily NO_2 concentrations. In Lima, NO_2 concentrations decreased in the early days of the lockdown but increased thereafter [57].

Satellite image data from over 10,000 air quality monitoring stations in 27 countries demonstrate a 29 percent reduction in ground-level NO_2 with a 95 percent confidence interval [67]. In a study conducted by Bassani and colleagues to evaluate changes in NO_2 concentration during and after the lockdown in Rome, they used the Tropospheric NO_2 vertical column density (VCD) from the TROPOspheric Monitoring Instrument (TROPOMI). In this study, they observed that NO_2 concentration in rural background stations, urban background and urban traffic decreased by 20 %, 34% and 50%, respectively. The TROPOMI VCD also showed that the decrease in NO_2 concentration in urban areas was more than in rural areas (43% vs. 17%) [68]. Similarly, Donzelli et al. found that nitric oxide levels were dramatically decreased at seven air monitoring stations located in Valencia, Spain [69]. Several studies, such as Mahato et al., have revealed significant NO2 concentration fluctuations before and during the lockdown, with a reduction of 52.68 percent [12]. These findings are similarly in line with those provided in Baldasano's research, in which a considerable decrease in NO_2 concentrations of 62% and 50% was observed in Madrid and Barcelona, respectively [70]. In a study by Lovric and colleagues, they used machine learning techniques to assess air quality in Graz, Austria, during the COVID-19 lockdown. The researchers found that NO_2 concentrations dropped between 36.9% and 41.6%, which could be explained by a significant reduction in traffic during the lockdown [70]. A similar study using the same technique to assess air quality during the COVID-19 epidemic in six major Chinese cities found that NO_2 concentrations fell by 36-53% [71]. In general, most studies on ambient air quality have shown a decrease in NO_2 concentration.

6. Global O_3 Concentration During COVID-19 Pandemic

Ground-level ozone (O_3) is one of the most harmful photochemical pollutants because people who are exposed to these pollutants are more at risk for reduced lung function, respiratory problems, asthma, and pulmonary diseases. Ozone is classified as a secondary pollutant because it is not emitted directly to the air from major urban pollution sources. It is a product of the chemical reaction between nitrogen oxides (NO_x) and volatile organic compound (VOC) materials. This process is carried out in the presence of sunlight and specific meteorological conditions. The main sources of VOCs and NO_x are chemical solvents, industrial facilities, and traffic. In addition to its health effects, O_3 is one of the most major short-lived air pollutants and one of the most significant greenhouse gases [22, 44, 72].

However, O_3 concentrations show different behavior compared to the other pollutants since a number of studies have shown that its concentration increased during the lockdown period [44]. For instance, one of the studies we reviewed shows that O_3 concentrations increased in Milan-Italy (12–86%), Seoul-South Korea (2–33%), and Wuhan-China (31–50%) during the COVID-19 lockdown. While NO_2 has decreased significantly, wind speed and temperature in 2020 compared to 2019 in those cities except Seoul have remained almost constant. This could be due to reduced NO_x emissions and meteorological conditions. However, O_3 levels dropped by 25% and 10% during the lockdown in Washington, DC, and Seattle, respectively. Also, in this study, no significant changes in O_3 concentration were observed for Lyon-France, Berlin-Germany and Sydney-Australia [22]. In a study conducted by Kumari et al., it was found that the O_3 level was increased in most cities, like Wuhan, Rome, Madrid, Sao Paulo, Beijing, Lima, Delhi, London, Moscow, and Las Vegas, while reduced in Mumbai and Bengaluru, during the lockdown period [57]. The increase in O_3 concentration may be due to the decrease in the availability of NO_x and VOCs, which leads to a decrease in O_3 consumption by NO (nitrogen monoxide) under the titration process. Another reason for this increase could be local meteorology, including temperature, sunlight, etc. On the other hand, this study reported that the reason for the decrease in O_3 emissions in Bengaluru and Mumbai is low temperatures and heavy rainfall during the lockdown [21, 73]. Another study conducted by Sicard et al. confirmed the results of the above-mentioned study. The average daily O_3 concentration during the lockdown in Rome, Wuhan, Turin, Nice, and Valencia decreased by 14%, 36%, 27%, 24%, and 2.4%, respectively, compared to the previous year [74]. Another study of 10 cities showed that O_3 concentrations decreased only in Rome [10%) [4]. In a study conducted by Kaviani Rad et al., they found that O_3 emissions in Iran increased by 12% [75]. Keller et al. used the machine learning technique to analyze changes in O_3 concentration in 46 countries during the COVID-19 lockdown. In this study, although the O_3 levels increased by up to 50% in some places, it was found that the overall net effect on the daily mean O_3 levels was low between February and June 2020 [76]. In general, most studies on ambient air quality have shown an increase in O_3 concentration.

7. Global SO_2 Concentration During COVID-19 Pandemic

Sulfur dioxide (SO_2) is a reactive, colorless air pollutant produced by sulfur and oxygen. The major sources of SO_2 production include the smelting of sulfur-containing mineral ores and the combustion of fossil fuels [77]. Exposure to SO_2 can cause respiratory disorders, lung dysfunction, and eye irritation. It is also known that exposure to this gas can aggravate some previous diseases, such as asthma and chronic bronchitis. In addition, SO_2 increases the risk of infectious diseases and hospitalization. The reaction of SO_2 with water molecules in the air causes the formation of sulfuric acid, which is a major component of acid rain and can damage forests, soils, and freshwater. In addition, SO_2 has a significant impact on the global and regional climate by forming sulfate aerosols [78-80].

Several researchers investigated changes in SO_2 concentrations. Changes in SO_2 levels were varied in these studies. For example, a study by Gope et al. showed a significant reduction in SO_2 concentrations in Wuhan, Madrid, Mumbai, Los Angeles, Seoul, and New York decreased by 42%, 50%, 33%, 33%, 50%, and 33%, respectively [4]. Otmani et al. also reported that the average SO_2 concentration in Sale city decreased by 49% [64]. However, in a study by Sharma et al., which evaluated the air quality of 22 cities in India during the lockdown, they found that changes in SO_2 concentrations were negligible [81]. Although SO_2 concentration has decreased in most of the evaluated studies, in a study in Iran, it was found that SO_2 concentration in Tehran has increased by 15% [75]. In general, most studies on ambient air quality have shown a decrease in SO_2 concentration.

8. Global CO Concentration During COVID-19 Pandemic

Carbon monoxide (CO) is an atmospheric pollutant with a significant role in atmospheric chemistry. For example, it participates in forming ground-level ozone. CO is predominantly eliminated by OH, and its lifetime weeks to months) is relatively long in comparison to other air contaminants. Biomass combustion and anthropogenic emissions are the primary sources of CO in the atmosphere, particularly when carbon fuels are not completely burnt [82-84].

A study by Habibi et al. found that CO concentrations decreased in Wuhan-China (2.5%-26%), Seoul-South Korea (18%), and Lima-Peru (61%). However, when compared to 2019, the CO level in Washington, D.C. increased by more than 50% in February 2020, then decreased by 4% in March 2020, and then by 20% in April 2020 [22]. In a study conducted in Tehran, Iran, it was found that CO levels decreased between 5% and 41% in different regions of Tehran during the COVI-D-19 pandemic. In another study in Rio de Janeiro, Brazil, researchers found that CO levels dropped between 30.3% and 48.5% [59]. In one study, Hu et al. used a machine learning technique to assess air quality and found that CO levels were reduced by 35.1% [85]. In general, most studies on ambient air quality have shown a decrease in CO concentration.

9. Impact of COVID-19 on Land Surface Temperature

The rise in air pollution and the resulting local climate change have become a major concern for municipal administrations. The release of pollutants into the atmosphere and growing urbanization disrupt the thermal balance of the atmosphere and earth's surface [86, 87].

Due to the COVID-19 lockdown, governments have imposed limitations on industrial activities and transportation system. The lockdown process reduces environmental pollution and promotes the development of a society with less environmental pollution. The positive effect of this lockdown has been observed in the rapid growth of vegetation and the reduction of air temperature and land surface temperature [88, 89]. LST is referred to as an important parameter in land surface processes because it serves as an indication of climatic change and controls the surface sensible, upward terrestrial radiation, and latent heat flux exchange with the atmosphere. In a study by Sahani et al., they found that the lowest and highest LST of Kolkata city, India before lockdown was 23.6°C and 36.6°C, whereas after lockdown it decreased to 17.3°C and 35.7°C, respectively [86]. A study by Guha et al., which examined the impact of the COVID-19 lockdown on LST in Raipur, India, found that the average value of LST in April and May fell by 5.3°C and 2.30°C, respectively, compared to previous years. This result represents a positive change in the lockdown phase, which the authors attribute to low population density and reduced road traffic [88]. Another study in India in with this study, which reported that the average LST dropped by 3°C to 5°C [90].

One of the most important factors affecting air quality is air transportation, which contributes approximately 1% to 2% of global greenhouse gas emissions and approximately 3% to 5% of global carbon dioxide (CO_2) emissions. Travel restrictions prompted a 63% drop in total flights and a 75% drop in commercial flights between January 23 and April 21, 2020. The sharp decline in mid-term and short-term aviation travel will reduce greenhouse gas emissions, especially CO_2. Due to the reduced greenhouse effect, the reduction of contrails will most likely result in a fall in air temperature [3]. However, in a study by Forster et al., they estimated that the direct impact of the lockdown on air temperature will be negligible, with cooling of around 0.01 ± 0.005°C by 2030 [91].

10. Conclusion

The COVID-19 pandemic has decreased pollution concentrations as a result of factory and business closures, along with social distancing and stay-at-home orders, which reduced the number of airplanes in the sky and the number of vehicles on the road. Although most studies have found considerable reductions in pollutants, we believe that due to the lack of some analysis data, these findings should be regarded with accuracy and caution. In the evaluated studies, different methods have been used that make it difficult to compare different results. For example, some studies have examined data on weather change during and before lockdown, but some studies have compared this data with average concentrations over the past 5 years. In the case of land surface temperature, although some studies show a decrease in LST, the analysis of these changes requires a long-term study.

However, it can be concluded that the restrictions and lockdown policies have generally reduced the concentrations of PM_{10}, $PM_{2.5}$, CO, NO_2, O_3, and SO_2. However, in most studies, the concentration of O_3, unlike other pollutants, has increased due to reduced NO_x emissions and meteorological conditions. Also, the land surface temperature [92] level has decreased in some areas, which has been negligible and requires long-term follow-up. Although continued lockdown can temporarily improve air quality and reduce air temperature, it is not a solution to improve the air quality that kills millions annually, and appropriate policies should be adopted to improve the weather conditions.

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