A Meta-Analysis on the Impact of COVID-19 Lockdown on Air Quality in High and Middle-Income Economies

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Abstract: Various studies have shown the positive impact COVID-19 had on the environment, but findings on different countries have yet to be reviewed together. The purpose of this paper is to perform a meta-analysis to provide a cross-country comparison of the impact of COVID-19 lockdown on air quality. 9 papers were chosen, providing data on at least 3 of the 6 major pollutants of some high-income and middle-income countries. A meta-analysis is then conducted to pool the results of multiple studies together to see if there is an overall trend. Data analysis demonstrates that the concentrations of $PM_{2.5}$, PM_{10}, NO_2, SO_2, and CO decreased and the concentration of O_3 increased in most countries. Lockdown reduced air pollution significantly in many countries, especially in middle-income economies. Research on what caused the more significant air pollution reduction in middle-income economies could be an interesting topic for further studies.

1 INTRODUCTION

The COVID-19 pandemic is one of the worst public health crises in modern history. The SARS-CoV-2 virus that caused the COVID-19 disease was first detected in Wuhan, China, in December 2019 and then spread rapidly across the globe. In an effort to curb its transmission, countries imposed various lockdown policies to restrict human and industrial activities which cost the global economy negatively. Nevertheless, lockdown brought benefits to the environment. Numerous studies have investigated the environmental effect of lockdown, but to my knowledge, this is the first paper that summarizes and compares relevant findings of both high-income and middle-income countries.

Thus, in this paper, the author conducts a country-level review of the environmental impact of COVID-19 lockdown by comparing countries' air pollution data before and after the implementation of lockdown policies in 2020. The purpose is to provide researchers with a synopsis of the air quality change during the lockdown and how the effect varied among countries with different income levels. Researchers can refer to this information for future studies related to air quality and large-scale lockdown.

The paper covers 8 countries with different lockdown timelines. India entered a nationwide lockdown on March 25, 2020, and lasted until May 3 (Mahato, Pal, Ghosh, 2020). In China, lockdown policies were imposed at the municipal level. The city of Wuhan, where COVID-19 was initially discovered, was the first to enter a lockdown on January 23 (Shi, Brasseur, 2020). The Iraqi government imposed a series of partial and total lockdowns starting March 1, 2020 (Hashim, Al-Naseri, Al-Maliki, Al-Ansari, 2021). Ecuador started a lockdown on March 17, 2020 (Zalakeviciute, Vasquez, Bayas, Buenano, Mejia, Zegarra, Diaz, Lamb, 2020). In Thailand, lockdown went into effect on March 26, 2020 (Stratoulias, Nuthammachot, 2020). European countries entered lockdown around mid- or late March 2020 (Balasubramaniam, Kanmanipappa, Shankarlal, Saravanan, 2020; Collivignarelli, Abbà, Bertanza, Pedrazzani, Ricciardi, Carnevale Miino, 2020; Jephcote, Hansell, Adams, Gulliver, 2021; Velders, Willers, Wesseling, den Elshout, van der Swaluw, Mooibroek, van Ratingen, 2021). The United States has never imposed a national-wide lockdown, but states set their own policies. California was the first state to issue a stay-at-home order starting March 19, 2020 (AJMC, MJH Life Sciences and Center For Biosimilars, 2020). Similarly, Canadian provinces and territories each followed a different timeline but generally entered lockdown around mid- or late March (Mashayekhi, Pavlovic, Racine, Moran,

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Manseau, Duhamel, Katal, Miville, Niemi, Peng, Sassi, Griffin, McLinden, 2021).

This review utilizes 6 major pollutants as indicators of air quality: particulate matter with diameters less than 2.5 µm ($PM_{2.5}$) and 10 µm (PM_{10}), nitrogen dioxide (NO_2), sulfur dioxide (SO_2), carbon monoxide (CO), and ozone (O_3). PM is a pollutant made up of a mixture of solid and liquid particles in the air. Its main source includes combustion engines, mining, and construction. Likewise, NO_2 and SO_2 are released from the combustion of fossil fuels in vehicles and other industrial activities. CO is another pollutant emitted from vehicles as well as home appliances such as furnaces, gas stoves, and dryers. O_3 can be good or bad for the environment and human health depending on where it is found in Earth's atmosphere. O_3 in Earth's upper atmosphere protects people from ultraviolet rays while ground-level ozone is harmful. This type of O_3 is produced when pollutants from vehicles and power plants chemically react in the presence of sunlight (Gupta, Tomar, Kumar, 2020).

Google Scholar was the source to search for the published papers with the following searched keywords: COVID-19, lockdown, and air quality. The articles were reviewed in their entirety, and a full article was obtained if they mentioned at least 3 of the 6 pollutants and indicated their trend. For each study, the percentage change in each air pollutant's concentration after a country's first lockdown was identified and summarized in Table 1 and Table 2.

Section 2 discussed findings on air quality changes in India, then presented findings on China, Iraq, Ecuador, Thailand, Europe, the United States, and Canada. Lastly, Section 3 provided a conclusion and suggested topics for future studies.

2 RESULTS AND DISCUSSION

The initial Google Scholar search retrieved 20 articles. After excluding publications that showed no percentage data on changes in pollutant concentrations, 9 articles were identified. 4 papers investigated the effect of lockdown on India's air quality, and the rest explored air quality changes in China, Iraq, Ecuador, Thailand, Europe, the United States, and Canada. All of these studies were published between 2020 and 2021.

2.1 India

During India's lockdown period, social gatherings were prohibited, employees and students were asked to work and learn from home, and transportation and industrial activities were shut down with exceptions to essential services. As a result, air pollution in Indian cities significantly reduced.

Mahato, Pal et al. 2020 (Mahato, Pal, Ghosh, 2020) looked into the impact of lockdown on Delhi's air quality using 7 air pollutant parameters. They obtained the daily or hourly concentrations of the pollutants before and during the lockdown from the Central Pollution Control Board (CPCB). The results showed decreasing trends in the average daily concentrations of PM_{10}, $PM_{2.5}$, NO_2, SO_2, and the average 8-hour concentration of CO by 52%, 53%, 53%, 18%, and 30% respectively. There was a slight increase in the average 8-hour concentration of O_3 by 0.78%.

A study conducted by Jain and Sharma 2020 (Jain, Sharma, 2020) focused on 5 Indian megacities. Likewise, they retrieved air quality data from the Central Pollution Control Board (CPCB) for five criteria air pollutants, i.e. $PM_{2.5}$, PM_{10}, NO_2, CO, and O_3, during both the pre-lockdown and lockdown periods.

Table 1: Percentage change in air pollutant concentrations in India.

Country/City	Author(s) and Year	Results
Delhi, India	Mahato, Pal et al. 2020 (Mahato, Pal, Ghosh, 2020)	-53.11% in $PM_{2.5}$, -51.84% in PM_{10}, -52.68% in NO_2, -17.97% in SO_2, -30.35% in CO, +0.78% in O_3
India (Delhi + 4 cities)	Jain and Sharma 2020 (Jain, Sharma, 2020)	-14-41% in $PM_{2.5}$, -34-52% in PM_{10}, -32-75% in NO_2, -16-46% in CO, +3-17% in O_3 in 4 cities but -11% in Bangalore
India (Delhi + 2 cities)	Kumari and Toshniwal 2020 (Kumari, Toshniwal, 2020)	Delhi: -49.34% in $PM_{2.5}$, -55.01% in PM_{10}, -60.11% in NO_2, -19.51% in SO_2, +37.35% in O_3 Mumbai: -37.35% in $PM_{2.5}$, -44.61% in PM_{10}, -78.12% in NO_2, -39.01% in SO_2, +20.65% in O_3 Singrauli: +15.27% in $PM_{2.5}$, +58.85% in PM_{10}, -12.50% in NO_2, +11.82% in SO_2, +35.07% in O_3
India	Bray, Nahas, et al. 2021 (Bray, Nahas, et al. 2021)	-43% in $PM_{2.5}$, -31% in PM_{10}, -18% in NO_2, -10% in CO, +17% in O_3

The results observed that, compared to pre-lockdown levels, the average daily concentrations of $PM_{2.5}$, PM_{10}, NO_2, and CO across the 5 cities decreased by 14-41%, 34-52%, 32-75%, and 16-46%. The trend for O_3 was not consistent for all cities as its average daily concentration increased in 4 cities by 3-17% but decreased in Bangalore by 11%.

Kumari and Toshniwal 2020 (Kumari, Toshniwal, 2020) investigated the concentrations of 5 key air pollutants in 3 Indian cities. Air quality data were collected locally before and after the lockdown from March to April 2020. The changes were similar in Delhi and Mumbai, where the average levels of PM_{10}, $PM_{2.5}$, NO_2, and SO_2 decreased by ~50%, ~43%, ~69%, ~29%, and the average level of O_3 increased by ~29%. Singrauli, however, did not experience a notable improvement in air quality.

Another study conducted by Bray, Nahas, et al. 2021 (Bray, Nahas, Battye, Aneja, 2021) examined improvements in air quality in India using the changes in the concentrations of 6 air pollutants. The air quality data for each area were collected from local satellite and ground-based measurements. Compared to the pollutants' average concentrations from 2015 to 2019, $PM_{2.5}$, PM_{10}, NO_2, and CO levels decreased by 43%, 31%, 18%, and 10% respectively, and O_3 levels increased by 17%.

Overall, as a result of restricted social and industrial activities during the national-wide lockdown, there have been significant reductions in the concentrations of 5 of the 6 major air pollutants $PM_{2.5}$, PM_{10}, NO_2, CO, and SO_2 in India. On the contrary, the concentration of O_3 increased because it varies inversely with the concentration of NO_2. When averaging the results from these 4 studies, $PM_{2.5}$ concentration decreased by 33.1%, PM10 concentration decreased by 30.6%, NO_2 concentration decreased by 46.9%, CO decreased by 24.6%, SO_2 decreased by 16.2%, and O_3 increased by 17.4%.

2.2 Other Countries

Besides India, other countries had also experienced notable improvements in air quality due to lockdown. There were 6 articles with detailed findings on China, Iraq, Ecuador, Thailand, Europe, the United States, and Canada.

Shi and Brasseur 2020 (Shi, Brasseur, 2020) quantified the changes in air quality in Wuhan, China, using data from the China National Environmental Monitoring Center for January and February 2020. The researchers found that when comparing the mean concentrations of 4 air pollutants before and after the city went into lockdown on January 23, the mean level of $PM_{2.5}$, NO_2, and CO decreased by 33%, 55%, 23% respectively. There was also a slight decline in the average daily concentration of SO2. For O3, its concentration increased by 108%.

Hashim, Al-Naseri, et al. 2020 (Hashim, Al-Naseri, Al-Maliki, Al-Ansari, 2021) analyzed the concentrations of 4 air pollutants, NO_2, O_3, $PM_{2.5}$, and PM_{10}, in Baghdad, Iraq. The air pollution data were collected from World Air Map for a period before lockdown from January to February 2020 and 4 periods of partial and total lockdown from March to July 2020. The post-lockdown pollution levels reflected a straight decrease in the average daily concentration of NO_2 by 20% and a straight increase in O_3 by 525%. $PM_{2.5}$ concentration fluctuated throughout the lockdown periods and resulted in a

Table 2: Percentage change in air pollutant concentrations in other countries.

Country/City	Author(s) and Year	Results
Wuhan, China	Shi and Brasseur 2020 (Shi, Brasseur, 2020)	-33% in $PM_{2.5}$, -55% in NO_2, -23% in CO, +108% in O_3
Baghdad, Iraq	Hashim, Al-Naseri, et al. 2020 (Hashim, Al-Naseri, et al., 2020)	-3% in $PM_{2.5}$, +56% in PM_{10}, -20% in NO_2, +525% in O_3
Quito, Ecuador	Zalakeviciute, Vasquez, et al. 2020 (Zalakeviciute, Vasquez, et al., 2020)	-29% in $PM_{2.5}$, -68% in NO_2, -48% in SO_2, -38% in CO
Hat Yai, Thailand	Stratoulias and Nuthammachot 2020 (Stratoulias and Nuthammachot, 2020)	-21.8% in $PM_{2.5}$, -22.9% in PM_{10}, -33.7% in NO_2, 9.9% in CO, -12.5% in O_3
Europe	Bray, Nahas, et al. 2021 (Bray, Nahas, et al., 2021)	-15% in $PM_{2.5}$, -10% in PM_{10}, -32% in NO_2, -10% in SO_2, -10% in CO, +7% in O_3
United States		-6% in $PM_{2.5}$, -22% in NO_2, -35% in SO_2, +7% in CO, +11% in O_3
Canada	Mashayekhi, Pavlovic, et al. 2021 (Mashayekhi, Pavlovic, et al., 2021)	-13.7% in $PM_{2.5}$, -38.7% in NO_2, +19.6% in O_3

slight reduction of 3%. On the contrary, PM_{10} only decreased initially by 15% and ended in a 56% overall increase.

Zalakeviciute, Vasquez, et al. 2020 (Zalakeviciute, Vasquez, Bayas, Buenano, Mejia, Zegarra, Diaz, Lamb, 2020) investigated the impact of restricted human activity on the air quality of Ecuador's capital Quito. The authors collected atmospheric pollution data from monitoring stations across Quito. The sampling period spanned 4 months and was separated into 2 periods before and after the national-wide lockdown. The results found a clear reduction in the average concentrations of NO_2, SO_2, CO, and $PM_{2.5}$, where each dropped by 68%, 48%, 38%, and 29%.

Stratoulias and Nuthammachot 2020 (Shi, Brasseur, 2020) investigated the temporal development of atmospheric constituent concentrations in Hat Yai, Thailand, from December 2019 to May 2020. Data on the concentrations of CO, NO_2, SO_2, O_3, PM_{10}, and $PM_{2.5}$ were obtained from a ground station in Hat Yai. When comparing the mean of pollutant concentrations 3 weeks before and 3 weeks after lockdown, CO concentration increased by 9.9%, NO2 concentration decreased by 33.7%, O3 concentration decreased by 12.5%, $PM_{2.5}$ concentration decreased by 21.8%, and PM_{10} concentration decreased by 22.9%.

Bray, Nahas, et al. 2021 (Bray, Nahas, Battye, Aneja, 2021) studied the changes in the concentrations of 6 air pollutants in Europe and the United States using satellite and ground-based measurements. For Europe, when the average concentrations of the pollutants in March 2020 were compared to their average levels for the same month from 2015 to 2019, the concentrations of $PM_{2.5}$, PM_{10}, NO_2, CO, and SO_2 decreased by 15%, 10%, 32%, 10%, and 10% respectively, and the concentration of O_3 increased by 7%. For the United States, the concentration of $PM_{2.5}$ decreased by 6%, NO_2 decreased by 22%, CO increased by 7%, SO_2 decreased by 35%, and O_3 increased by 11%.

Mashayekhi, Pavlovic, et al. 2021 (Mashayekhi, Pavlovic, Moran, Manseau, Duhamel, Katal, Miville, et al. 2021) investigated the impact of lockdown on Canada's 4 largest cities. Data on surface concentrations of $PM_{2.5}$, NO_2, and O_3 were obtained from local air quality monitoring networks under the National Air Pollution Surveillance (NAPS) program. Researchers compared the mean concentration of each pollutant for the pre-lockdown and lockdown periods in 2020 and found that $PM_{2.5}$ and NO_2 concentrations decreased by 13.75% and 38.7% and O_3 concentration increased by 19.6%.

In summary, most of the countries reviewed in Section 2, including India, experienced similar trends in the changes of concentrations of the air pollutants: $PM_{2.5}$, PM_{10}, NO_2, CO, and SO_2 levels reduced, and O_3 levels grew. However, there were a few exceptions. Iraq, for example, underwent significant growth in its PM_{10} concentration (56%) instead of a decrease. It also experienced much greater growth in

Table 3. Average percentage change in air pollutant concentrations in high-income countries.

Country	Author(s)	$PM_{2.5}$	PM_{10}	NO_2	CO	O_3	SO_2
Europe	Bray, Nahas, et al. 2021(Bray, Nahas, Battye, Aneja, 2021)	-15%	-10%	-32%	-10%	7%	-10%
United States		-6%	-	-22%	7%	11%	-35%
Canada	Mashayekhi, Pavlovic, et al. 2021 (Mashayekhi, Pavlovic, et al., 2021)	-13.7%	-	-38.7%	-	19.6%	-
Average		-11.6%	-10.0%	-30.9%	-1.5%	12.5%	-22.5%

Table 4: Average percentage change in air pollutant concentrations in middle-income countries.

Country	Author(s)	$PM_{2.5}$	PM_{10}	NO_2	CO	O_3	SO_2
India	(averaged)	-33.08%	-30.56%	-46.88%	-24.59%	17.44%	-16.17%
China	Shi and Brasseur 2020 (Shi and Brasseur, 2020)	-33%	-	-55%	-23%	108%	-
Iraq	Hashim, Al-Naseri, et al. 2020 (Hashim, Al-Naseri, et al., 2020)	-3%	56%	-20%	-	525%	-
Ecuador	Zalakeviciute, Vasquez, et al. 2020 (Zalakeviciute, Vasquez, et al., 2020)	-29%	-	-68%	-38%	-	-48%
Thailand	Stratoulias and Nuthammachot 2020 (Shi, Brasseur, 2020)	-21.8%	-22.9%	-33.7%	9.9%	-12.5%	-
Average		-24.0%	0.8%	-44.7%	-18.9%	159.5%	-32.1%

its O_3 concentration by more than 5 times while O_3 levels only increased by ~10-20% in other countries. Thailand also observed an opposite trend in its O_3 concentration which declined by 12.5%. Besides, the United States saw a slight increment in its CO concentration instead of a reduction.

In addition, all the above countries were categorized into high-income and middle-income economies according to the World Bank's country classifications. The purpose was to examine whether the two groups differed in their degrees of air quality improvement. The high-income economies include Europe, the United States, and Canada, and the middle-income countries include India, China, Iraq, Ecuador, and Thailand. Table 3 and Table 4 showed each pollutant's average percentage change in their concentration and the results showed that the middle-income economies experienced more substantial reductions in air pollutants after lockdown. In middle-income economies, the percentage changes in $PM_{2.5}$, NO_2, CO, O_3, and SO_2 were 2.1, 1.4, 12.6, 12.8, and 1.4 times greater than the percentage changes in high-income economies. However, the average PM_{10} concentrations in middle-income economies slightly increased compared to a decline in high-income economies. This anomaly can be explained by Iraq's expansion in its PM_{10} level during the lockdown which was an outlier to PM_{10} statistics, skewing the average concentration to the right. Figures 1 and 2 provide direct visualization of the percentage change in air pollutants, i.e. $PM_{2.5}$ and NO_2, versus income of a country. The author uses the 2021 GDP per capita from IMF World Economic Outlook database as an indicator of income level. In general, middle-income economies see a more significant improvement in air pollution than high-income economies.

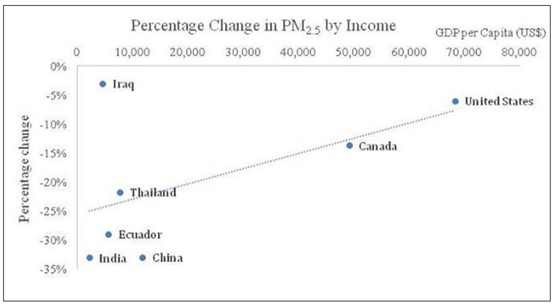

Figure 1: Scatter plot of percentage change in $PM_{2.5}$ by GDP per capita.

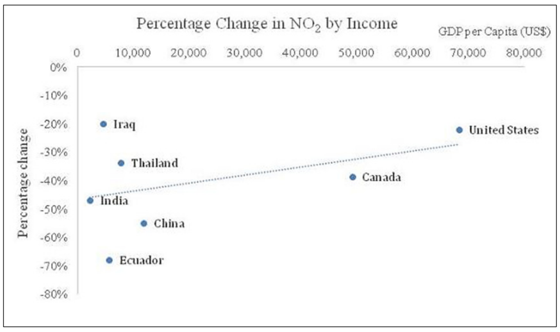

Figure 2: Scatter plot of percentage change in NO2 by GDP per capita.

Nevertheless, there is not yet a paper that addresses why the percentage changes in air pollutant concentrations in middle-income economies are higher than those in high-income economies. One implication, though, could be that not all sources of pollution were affected by the lockdown; the ones most impacted by lockdown could be more prevalent in some countries but less common in others. For example, $PM_{2.5}$ could originate from the burning of fossil fuels and biomass or from windblown dust, but lockdown could have impacted these sources to different degrees depending on each country's situation (Narain, 2020). To find out the cause of the difference in air quality changes in high-income and middle-income economies, researchers could look into the extent to which each pollutant's sources are affected in different countries for further studies.

3 CONCLUSION

COVID-19 lockdown produced notable environmental benefits for countries around the world. The impact was evident from a reduction in the concentration of air pollutants such as $PM_{2.5}$, PM_{10}, NO_2, CO, and SO_2 and growth in the concentration of O_3 in most countries. This result suggests that the environment could self-recover during a period of restricted human movements and industrial activities. In addition, middle-income economies experienced a greater percentage decrease in air pollutant concentrations than high-income economies, which could be the result of higher levels of air pollution these countries originally endured or differences in the countries' major sources of pollution, such as traffic, industrial, and natural. Future research could explore how lockdown affected different sources of air pollution in high-income and middle-income countries to find out why the difference in air quality change existed between the two groups. Researchers could also compare the changes in air pollution levels against changes in transportation, human movements, and domestic production to find out how these factors contributed to improvements in air quality.

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