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The Impact of COVID-19 Lockdowns on the Air Quality in Major Cities Across the World:
A Brief Review

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Abstract

The COVID-19 lockdowns provided the opportunity to ascertain the contribution of anthropocentric activities to local and global air pollution. Major pollutants tackled in published studies were particulate matter (PM), sulfur dioxide (SO_2), nitrogen dioxide (NO_2), ground-level ozone (O_3) and carbon monoxide (CO). Generally, the lockdowns reduced emissions from the transport and manufacturing sectors, thereby resulting in decreased levels of pollutants, except for O_3 which increased in most cities potentially due to the decrease of PM, NO_2 and VOC. Overall, the results of the studies revealed improved air quality during the COVID-19 lockdowns but was not sustained as indicated by the gradual resumption to its pre-COVID level with the easing of restrictions. Moreover, the changes in the pollution level during the lockdowns were also potentially influenced by atmospheric chemistry involved in the formation of secondary pollutants and by prevailing meteorological factors, specifically temperature, humidity and wind speed and direction. Hence, these factors should also be considered in formulating sustainable air pollution control strategies by local, national and international policy makers.

Keywords: Air pollution, Quarantine impact, Pollution, Particulate matter, Ozone, Carbon dioxide

1. Introduction

Based on particulate matter, the countries with the most polluted cities include Bangladesh, Pakistan, Mongolia, Afghanistan, India, Iraq and mainland China, among others (IQAir, 2019). Based on the list, South Asia, Southeast Asia and Western Asia are the regions with the most problematic air quality, with only 6 out of 355 cities meeting World Health Organization (WHO) annual targets of $PM_{2.5}$ content (10 µg/m^3). This problem of air pollution is primarily due to anthropocentric activities driven by rapid population growth (Ghosh et al., 2020) and typically comes from sources such as power generation, traffic, industry and residential energy use (Venter et al., 2020).

Based on their sources, pollutants in the air can be classified as primary or secondary pollutants. Primary pollutants include sulfur dioxide (SO_2), nitrogen oxides (NO_x) and nitrogen dioxide (NO_2) which are emitted to the atmosphere directly from burning of fossil and nonconventional fuels like biomass and other high-temperature industrial processes (Sharma et al., 2020). Similarly, carbon monoxide (CO) is formed from incomplete combustion of fuels, from both mobile and stationary applications (Brook et al., 2010, Sharma et al., 2020).

Combustion of fuels, whether conventional or nonconventional also results in the formation of coarse

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particles containing both organic and inorganic components which get suspended in the air and termed as particulate matter (PM) (Sharma et al., 2020). In addition, PM, whose size and composition vary (Pöschl, 2005), may also come from natural sources, agricultural emissions, industrial processes (i.e. power plants, manufacturing) and even wind-blown dust from roads and construction activities (Brook et al., 2010, Kampa and Castanas, 2008). PM are often reported as $PM_{2.5}$ and PM_{10} which correspond to the size of the particles with aerodynamic diameter smaller than 2.5 µm and 10 µm, respectively. Aside from the size, the composition of PM also vary since they can absorb and transfer different types of pollutants in the air, but are generally composed of metals, organic compounds and gases (Pei et al., 2020, Pöschl, 2005). Karagulian et al. (2015) estimate that on a global scale, 25% of the urban air pollution from $PM_{2.5}$ is from traffic, while 15% is from industrial activities, 20% from domestic fuel burning, 18% from natural dust and salt and 22% from unspecified human sources.

Secondary pollutants, on the other hand, are those that are formed through the chemical reactions of primary pollutants in the atmosphere, with the aid of sunlight, water vapor and clouds (Brook et al., 2010). Example of which is ozone (O_3) which may be formed through the reaction of nitrogen oxide (NO_x) with carbon monoxide (CO) (Sharma et al., 2020). Volatile organic compounds (VOCs) like benzene, toluene, xylene, and polycyclic aromatic hydrocarbons which are typically from industries (i.e. primary pollutants) may undergo different reactions in the atmosphere and may contribute to the formation of O_3 and association to PM (Brook et al., 2010, Kampa and Castanas, 2008). Meanwhile, nitrogen dioxide (NO_2) may also be a secondary pollutant as it can be formed through the reaction of NO_x and O_3. Aside from O_3, other secondary pollutants include sulfate, nitrate and ammonium associated with PM (Sitaras and Siskos, 2008). Also considered as secondary pollutants are inorganic and organic acids like hydroxyl radical, peroxyacetyl nitrate, nitric acid, formic acid and acetic acid, to name a few (Brook et al., 2010).

As it is estimated that about 92% of the world population breathe air with poor quality (World Health Organization, 2018), it has become a major cause of acute and chronic diseases, and even death among humans. It has the fifth highest mortality risk factor globally and is associated with approximately 4.9 M deaths in 2017 (Health Effects Institute, 2019). In general, it affects different systems and organs, most particularly respiratory and cardiovascular systems (Brook et al., 2010, Kampa and Castanas, 2008, Pope and Dockery, 2006). Depending on exposure, concentration of pollutants, age, nutritional status and predisposing conditions of the person exposed to pollution, health effects may include nausea, breathing difficulty, eye and skin irritation to long-term chronic diseases like cancer (Ghorani-Azam et al., 2016, Kampa and Castanas, 2008). Ghorani-Azam et al. (2016) discuss in greater detail how the major pollutants in the air such as PM, ground-level O_3, CO, SO_2, NO_x and other pollutants affect human health and is therefore not discussed in this review.

The focus of this review is on the effect of the COVID-19 lockdowns on the air quality in major cities around the world, with emphasis on the major pollutants discussed above. Specifically, it focuses on how the lockdowns changed the level of each major pollutant of interest. However, this review does not intend to intercompare changes that occurred in each city or country during the lockdowns. Consequently, this review also provides insights, specifically to policy makers, as to whether temporary lockdowns can sustainably decrease local and global air pollution levels.

2. COVID-19 Lockdown and its Importance

When COVID-19 illness caused by severe acute respiratory syndrome corona virus (SARS-CoV-2) was declared as a global pandemic by the WHO on March 11, 2020 (Al-Qahtani, 2020), the initial response of governments across the world was directed towards preventing disease transmission. The effort was termed as “flattening the curve” and was also done to relieve pressure on the health care system (Wang et al., 2020b). As recommended by the WHO, state of emergency was declared and unprecedented lockdowns were imposed in many countries.

Although the features of the lockdown vary from cities to cities and countries to countries, the measure was generally characterized by restricting movement and mobility as well as avoiding social and mass gatherings. Schools, shopping malls, theatres, libraries, factories, construction projects and non-essential sectors were closed, curfews were imposed, gatherings were limited to five people and outdoor recreational activities were prohibited (Adams, 2020, Mor et al., 2021). Work-from-home was encouraged and only those sectors providing essential services to the community (i.e. food, groceries, and medicines) were allowed to operate as usual while observing precautionary measures (Li and Tartarini, 2020, Sharma et al., 2020).

Some countries like Singapore also banned entries of short-term international visitors (Li and Tartarini, 2020). Similarly, India imposed travel bans on all modes of transport, whether by air, land or water (Resmi et al., 2020, Sharma et al., 2020). In Ecuador, vehicles are only allowed to travel one day per week, within a specific time frame (05:00 to 14:00) depending on their plate numbers (Zambrano-Monserrate and Ruano, 2020).

As a result of these restrictions, movement of vehicles and operation of most industries (manufacturing, tourism, construction, mining, etc.) were significantly reduced (Mahato et al., 2020). For example, Google Mobility Report indicated that lockdown measures in Ontario, Canada and in Mexico City Metropolitan Area result in an overall change in transportation movements specifically indicated by the reduction of time spent in retail and recreational areas, grocery and pharmacy, parks, transit stations and workplace, while increasing the time spent in residential areas (Adams, 2020, Hernández-Paniagua et al., 2021).

Although the lockdown measures which halted most economic activities drastically affected the world economy (Ozili and Arun, 2020, Filonchyk et al., 2020), the lockdown period provided an opportunity to conduct research works that further establish the impact of anthropocentric activities on the environment. Specifically, the shutdown of transport, manufacturing and other industries enable the investigation of their impact on air quality, specifically on estimating how much improvement on air quality can be achieved with their shutdown (Anil and Alagha, 2020, Dobson and Semple, 2020, Kerimray et al., 2020, Ordóñez et al., 2020), and whether imposing lockdown measures and mobility policies can be a practical way to combat air pollution problems and restore environmental quality particularly in urban cities (Baldasano, 2020, Kumari and Toshniwal, 2020b). In addition, it also enables the study of the relationship between baseline air pollution and natural processes (Dhaka et al., 2020) and may help policymakers in formulating short-term and long-term environmental policies, specifically atmospheric governance policies that will address the issue of air pollution (Anil and Alagha, 2020, Pei et al., 2020, Selvam et al., 2020).

3. Source of Data

The air pollution data used by the different studies reviewed in this paper are either satellite data (Miyazaki et al., 2020), data from monitoring sites or ground-based observatory (Anil and Alagha, 2020, Baldasano, 2020, Silver et al., 2020) or combination of both (Dang and Trinh, 2020, Hernández-Paniagua et al., 2021). Pei et al. (2020) noted that although satellite data are generally affected by cloud cover, the general trends obtained from such source are comparable to that of ground-based data from monitoring sites. Ground data from monitoring stations are usually advantageous as they come with relevant information on site types and are therefore more reflective of actual situations in the emission sources (Venter et al., 2020). On the other hand, satellite data which can show air quality on a regional and global scale may be limited by coarse spatial resolution which does not enable comparison among site types (example between roadsides and suburban areas)(Jephcote et al., 2021). Satellites which have been sources of data of the studies reviewed here include:

(1) Sentinel-5P (Islam and Chowdhury, 2021) which used the TROPOMI (Tropospheric Monitoring Instrument) instrument capable of measuring concentration of different gases in the atmosphere (Islam and Chowdhury, 2021, Morales-Solís et al., 2021). Generally, satellite (Sentinel-5P) and ground data from monitoring stations follow the same temporal pattern (Stratoulias and Nuthammachot, 2020).

Data considered were those from pre-lockdown, lockdown and post-lockdown periods. Historical data from 2014-2019 were also used for comparison, specifically in examining long-term trends and to ascertain that the changes in air quality was primarily due to the lockdown measures and not due to favorable meteorological conditions during these periods (Higham et al., 2020, Kerimray et al., 2020, Silver et al., 2020). Comparing data collected during the lockdowns of 2020 to historical data could also reduce the inter-annual variability in terms of the air pollutants and meteorological variables (Morales-Solís et al., 2021).

Studies focusing on cities in different countries were included in the review to ensure that information on how air quality was changed during the lockdown periods will be as conclusive and as comprehensive as possible.

4. Discussion

4.1 Effect of Lockdown on Each Pollutant

Generally, the lockdown measures result in improvement in air quality in many parts of the world as demonstrated in various studies (Table 1). Table 1 shows the different air pollution studies in different cities across the world, highlighting the effect of lockdown measures on major air pollutants as identified by Central Pollution Control Board of India. These pollutants are PM, ground-level O_3, NO_2, SO_2 and CO (Ghosh et al., 2020). The following sections tackle each of these pollutants.

4.1.1 Particulate Matter

In all cities where air quality was monitored, PM concentration decreased during the lockdown period (Table 1). On a national level in China, the average reduction in PM_{10} and $PM_{2.5}$ was about 32% and 15%, respectively (Zheng et al., 2020). In over 44 cities in Northern China, the decrease was in the range of 5 – 14% (Bao and Zhang, 2020). In Wuhan, the first to impose lockdown measures, PM concentration for the lockdown period decreased by 37% when compared to the same period in 2019 and was higher than the national average. Moreover, the chloride and nitrate composition of the $PM_{2.5}$ showed about 0.85 μg/m^3 (~ 30% reduction) and 9.86 μg/m^3 (~ 40% reduction) reduction, respectively (Zheng et al., 2020). These reductions, along with decrease in hydrocarbon-like organic aerosols were also observed by Chen et al. (2020a) for air quality data in Shanghai, due to the reduction in primary emissions brought about by restricted anthropogenic activities.

Although primary emission of PM was reduced due to reduction in vehicular traffic and halting of industrial activities (Collivignarelli et al., 2020) as indicated by decreased in the trace elements (TE) and elemental carbon (EC) components of PM, secondary formation was enhanced during the lockdown (Chen et al., 2020a, Wang et al., 2020a, Zheng et al., 2020). This secondary formation was due to the contribution of secondary inorganic aerosol (SIA) (i.e. sulfate, oxygenated organic aerosol) with increased mass percentages of about 3 – 8% during the lockdown period (Chen et al., 2020a, Zheng et al., 2020). Formation of secondary aerosol is enhanced by favorable meteorological condition, specifically low wind speed and high humidity (Wang et al., 2020a). For example, sulfate is known to be hydrophilic therefore promotes heterogeneous reactions under humid condition (Wang et al., 2012). With these observations, it is necessary that the chemistry behind the formation of secondary aerosol and how it is affected by meteorological factors are understood, specifically in formulating air pollution control strategies that are aimed at reducing primary emission.

Table 1 Summary of changes in the concentration of major pollutants in different cities, countries and regions across the world as influenced by the COVID-19 lockdowns

Reference	City/Country/ Region	Source of data	Period covered by the study	Percent reduction (-) or increase (+) in the concentration of pollutants				
				$PM_{2.5}$ and PM_{10}	O_3	NO_2	SO_2	CO
Sharma et al. (2020)	Rajasthan, India (Ajmer, Alwar, Bhiwadi, Jaipur, Jodhpur, Kota and Udaipur)	Monitoring stations	Pre-LD: Mar 10 – 20, 2020 LD: Mar 25 – May 17, 2020	$PM_{2.5}$: (-) 37.1 PM_{10}: (-) 35.2	(+) 7.75	(-) 49	(-) 19.7	--
Dhaka et al. (2020)	Delhi, India	Monitoring stations	Pre-LD: Mar 1– 24, 2020 LD: Mar 25 – Apr 14, 2020	$PM_{2.5}$: (-) 50 ± 15	(+) 30 - 40	(-) 60 - 70	(-) 25	(-) 25 - 66
Nigam et al. (2021)	Western India (Ankleshwar, Gujarat, India)	Central Pollution Control Board	LD: Mar 25 – May 31, 2020 (compared with the same period in 2019)	$PM_{2.5}$: (-) 6 to (-) 36 PM_{10}: (+) 24 to (-) 29	(-) 31 to (+) 192	(+) 27 to (-) 80	(-) 28 to (-) 67	(+) 30 to (+) 150
Nigam et al. (2021)	Western India (Vapi, Gujarat, India)	Central Pollution Control Board	LD: Mar 25 – May 31, 2020 (compared with the same period in 2019)	$PM_{2.5}$: (-) 19 to (-) 48 PM_{10}: (-) 21 to (-) 52	(-) 36 to (+) 310	(-) 43 to (-) 91	(+) 7 to (-) 81	(-) 18 to (+) 132
Zheng et al. (2020)	Wuhan, China	Monitoring stations	Jan 23 – Feb 22, 2020 (compared with the same period in 2019)	$PM_{2.5}$: (-) 37	--	--	--	--
Chen et al. (2020b)	United States of America	Monitoring stations	LD: Mar 15-Apr 25,2020 (compared with pre-lockdown period and 2017-2019 data)	--	--	(-) 49	--	(-) 37
Selvam et al. (2020)	Gujarat State, India	Monitoring stations	Pre-LD: Jan 1 – Mar 23, 2020 LD: Mar 24 – Apr 20,2020 (compared with the same period in 2019)	$PM_{2.5}$: (-) 38 - 78 relative to pre-LD; (-) 39 relative to 2019 data	(+) 16 -48 relative to pre-LD (+) 58	(-) 30 -84 relative to pre-LD (-) 59	(-) 22 – 58 relative to pre-LD (-) 40	(-) 3 – 55 relative to pre-LD (-) 25

				PM_{10}: (-) 32 - 80 relative to pre-LD; (-) 44 relative to 2019 data	relative to 2019 data	relative to 2019 data	relative to 2019 data	relative to 2019 data
Chen et al (2020)	Shanghai, China	Monitoring stations	Pre-LD: Jan 8 – 23, 2020 LD: Jan 24 – Feb 8, 2020	(-) 33 - 44	(+) exact amount not specified	(-) exact amount not specified	(-) 15	(-) 22
Zambrano-Monserrate and Ruano (2020)	Quito, Ecuador	Monitoring stations	Mar 25 – 31, 2020 (compared with the same period in 2018-2019)	(-) 147 - 164	(+) 148 - 179	(-) 480 - 560	--	--
Arshad et al. (2020)	Indo-Pak Region	Satellite data	Mar – May, 2020 (compared with 2015-2019 data)	--	--	(-) 40 -50	--	--
Otmani et al. (2020)	Sale City (Morocco)	Monitoring stations	LD: Mar 11 – Apr 2, 2020 (compared with pre-LD)	PM_{10}: (-) 75	--	(-) 96	(-) 49	--
Stratoulias and Nuthammachot (2020)	Hat Yai, Thailand	Monitoring stations and satellite data	Pre-LD: Mar 4-Mar 24,2020 LD: May 25-Apr 14,2020 (compared with 2010-2019 data)	$PM_{2.5}$: (-) 21.8 PM_{10}: (-) 22.9	(-) 12.5	(-) 33.7	No significant change	--
Adams (2020)	Ontario, Canada	Monitoring stations	Pre-LD and LD periods (compared with 2015-2019 data)	$PM_{2.5}$ not significantly lower than pre-LD and in previous years	--	Not significantly lower than pre-LD and	--	--
Pei et al. (2020)	Beijing, Wuhan, Guangzhousa	Satellite data and monitoring stations	Jan 23 – Mar 23, 2020 (compared with pre-LD and 2019 data)	Beijing: $PM_{2.5}$: (+) 50 – 214 Wuhan: (-) 28 -57 Guangzhou: no significant change	Beijing: (+) 33 Wuhan: (+) 60 -128 Guangzhou: (+) 7 - 50	Beijing: (-) 20 – 28 Wuhan: (-) 57 – 60 Guangzhou: 46	Beijing: (-) 33 Wuhan: (-) not significant Guangzhou: (-) not significant	--
Dobson and Semple (2020)	Scotland	Monitoring stations	LD: Mar 23 – Apr 22, 2020 (compared with 2017 – 2019 data)	$PM_{2.5}$: (-) 4.6 – 19.7	--	(-) 38 -41.5	--	--

Higham et al. (2020)	United Kingdom	Monitoring stations	LD: Mar 23 – June 30, 2020 (compared with 2013 – 2019 data)	$PM_{2.5}$: (-) 18	(+) 10	(-) 50	(+) 100	--
Silver et al. (2020)	across China	Monitoring stations	(compared with 2015 -2019 data)	$PM_{2.5}$: (-) 10.5 PM_{10}: (-) 21.4	(+) 5.1	(-) 27	--	(-) 7.8 – 16.5
Anil and Alagha (2020)	Eastern Province, Saudi Arabia	Monitoring stations	Pre-LD: Sept 15,2019 – Mar 22, 2020 LD: Mar 23 – June 20, 2020 Post LD: June 21 – July 18, 2020	PM_{10}: (-) 21 – 70%	(+) 6.3 -45	(-) 12 – 86	(-) 8.7 – 30	(-) 5.8 – 55
Jephcote et al. (2021)	United Kingdom (across the country)	Monitoring stations	LD: Mar 30,3030 to May 3,2020 (compared with 2017-2019 data)	$PM_{2.5}$: (-) 16.5	(+) 7.6	(-) 38.3	--	--
Dang and Trinh (2020)	Vietnam	Satellite data	LD: Apr 1 - 14, 2020 (compared to pre and post LD; Jan 1 – July 1, 2020)	--	--	(-) 24 - 32	--	--
Collivignarelli et al. (2020)	Milan, Italy	Monitoring stations	Pre-LD: Feb 7 – 20, 2020 Partial LD: Mar 9 – 22, 2020 Total LD: Mar 23 – Apr 15	$PM_{2.5}$: (-) 37.1 – 47.4 PM_{10}: (-) 32.7 – 59.4	(+) 117 - 193	(-) 40 - 58	(-) 6.8 – 19.9	(-) 32 – 57.6
Siciliano et al. (2020)	Rio de Janeiro, Brazil	Monitoring stations	Pre-LD: Mar 1 – 22, 2020 Partial LD: Mar 23 – Apr 5, 2020 Relaxed LD: Apr 6 – Apr 16, 2020	--	(+) 0.1 – 12.9	(-) 9.2 – 46.1	--	--
Baldasano (2020)	Barcelona and Madrid, Spain	Monitoring stations	LD: Mar 14 – Apr 30, 2020 (compared with 2018 – 2019 data)	--	--	Barcelona: (-) 55 – 59 Madrid: (-) 46 - 56	--	--
Kumari and Toshniwal (2020a)	Delhi, Mumbai and Singrauli	Monitoring stations	Pre-LD: Mar 1 -24, 2020 LD: Mar 25 – Apr 15, 2020	$PM_{2.5}$ Delhi: (-)49 Mumbai: (-) 37 Singrauli: (+) 15.27 PM_{10} Delhi: (-) 55	Delhi: (+) 37.35 Mumbai: (+) 20.65 Singrauli: (+) 35.07	Delhi: (-) 60 Mumbai: (-) 78 Singrauli: (-) 12.5	Delhi: (-) 19 Mumbai: (-) 39 Singrauli: (+)11.82	--

				Mumbai: (-) 44 Singrauli: (+) 58.85				
Cui et al. (2020)	Xianghe (rural site between Beijing and Tianjin)	Monitoring stations	Pre-LD: Jan 12 – 25, 2020 LD: Jan 26 – Feb 9 Post LD: Mar 22 – Apr 2, 2020	--	--	--	--	--
Ordóñez et al. (2020)	Europe	Monitoring stations	LD: Mar 15 – Apr 30, 2020 (compared with 2015 – 2019 data)	--	(+) 10 -22	(-) 5 - 55	--	--
Mor et al. (2021)	Chandigarh, India	Monitoring stations	LD: Mar 25 – May 17, 2020 (compared with 21 days pre-LD)	$PM_{2.5}$: (-) 1.1 – 28.8 PM_{10}: (-) 2.4 – 36.8	(+) 39 - 129	(-) 7 - 23	(+) 1 - 19	(-) 3 - 16
Hashim et al. (2021)	Baghdad, Iraq	Satellite data and World Air Pollution Map website	Pre-LD: Jan 16 – Feb 29, 2020 LD: Mar 1 – Jul 24, 2020	$PM_{2.5}$: (-) 2.5 – 8 PM_{10}: (-) 15 in the earlier LD phase; (+) 56 in the later phase	(+) 13 - 525	(-) 6 - 20	--	--
Islam and Chowdhury (2021)	Dhaka City, Bangladesh	Monitoring stations and satellite data	LD: Apr – May 2021 (compared with 2019 data)	$PM_{2.5}$: (-) 26	--	(-) 30	(-) 7	(-) 7
Kanniah et al. (2020)	South East Asian (SEA) Region (most especially Malaysia)	Satellite data and monitoring stations	(compared with 2018 – 2019 data)	$PM_{2.5}$: (-) 23 – 32 PM_{10}: (-) 26 - 31	--	Over SEA: (-) 27 – 30 Malaysia: (-) 63 -64 Singapore: 16 -30 Bangkok: (-) 1 -22 Jakarta: (-) 13 -34 Manila: (-)	(-) 9 - 20	(-) 25 -31

						30 -34 Vietnam: (-) 5 -9		
Li and Tartarini (2020)	Singapore	Satellite data and monitoring stations	LD: Apr 7 – May 11, 2020 (compared with 2016 – 2019 data)	$PM_{2.5}$: (-) 29 PM_{10}: (-) 23	(+) 18	(-) 54	(-) 52	(-) 6
Mahato et al. (2020)	Delhi, India	Monitoring stations	Pre-LD: Mar 2 – 21, 2020 LD: Mar 25 – Apr 14, 2020 (compared with 2019 data)	$PM_{2.5}$ and PM_{10}: (-) > 50% relative to Pre-LD $PM_{2.5}$: (-) 39 relative to 2019 data PM_{10}: (-) 60 relative to 2019 data	(+) 7 relative to Pre-LD	(-) 52.68 relative to Pre-LD	(-) 17.97 relative to Pre-LD	(-) 30 -35 relative to Pre-LD
(Morales-Solís et al., 2021)	16 cities in Central and Southern Chile	Monitoring stations and satellite data	LD: Mar 15-May 31,2020 (compared with 2017-2019 data)	$PM_{2.5}$: (-) 6 to 48 in 10 cities PM_{10}: (+) 14 to (-) 33 in 9 cities	(+) 18 to 43 in 4 cities	(-) 27 to 55 in 4 cities	--	--
Kerimray et al. (2020)	Almaty, Kazakhstan	Monitoring stations	Pre-LD: Feb 21 – Mar 18, 2020 LD: Mar 19 – Apr 14, 2020 (compared with 2018 – 2019 data)	$PM_{2.5}$: (-) 21 relative to pre-LD and (-) 28 relative to 2018 – 2019 data	(+) 15 relative to Pre-LD	(-) 35 relative to Pre-LD	(+) but not statistically significant	(-) 49 relative to Pre-LD
Resmi et al. (2020)	Kannur, South India	Monitoring stations	Pre-LD: Mar 1 – 25, 2020 LD: Mar 26 – Apr 20, 2020 Triple LD: Apr 21 – May 10	$PM_{2.5}$: (-) 53 PM_{10}: (-) 61	(+) 22	(-) 71	(-) 62	(-) 67
Ghahremanloo	East Asia (Beijing-	Satellite data	LD: Feb 2020 (compared with Feb	--	--	BTH: (-) 54	Wuhan: (-)	Wuhan: (-)

et al. (2021)	Tianjin-Hebei (BTH) Region, Wuhan, Seoul,Tokyo)		2019 data)			Wuhan: (-) 83 Seoul: (-) 33 Tokyo: (-) 19	71	4
Hernández-Paniagua et al. (2021)	Mexico City Metropolitan Area	Monitoring stations and satellite data	(compared with 2016-2019 data)	$PM_{2.5}$: (-) 32 PM_{10}: (-) 20	(+) 16-40	(-) 10-43	--	--
Wetchayont (2021)	Bangkok, Thailand	Monitoring stations	Pre-LD: Jan 1- Mar 25,2020 LD: Mar 26 – May 31,2020 After LD: June 1 – July 31,2020 (compared with 2019 data; before, during and after lockdown)	$PM_{2.5}$: (-) 0.7 to 20.7 PM_{10}: (-) 4.1 to 31.7	(-) 0.3 to 7.1	(+) 3..2 to 26.6	(+) 41.5 to 84.6	(-) 8 to 23.6

In India, the air quality improvement in major cities such as Delhi, Mumbai, Chennai and Kolkata was also investigated and all demonstrated a reduction in PM_{10} and $PM_{2.5}$ during the lockdown as compared to similar periods in 2019 (Ghosh et al., 2020). In Delhi, PM_{10} and $PM_{2.5}$ showed 60% and 39% reduction relative to the 2019 data, respectively. Meanwhile, in Western India, the $PM_{2.5}$ and PM_{10} concentration in 2020 also decreased by 39% (92 μg/m^3) and 44% (88 μg/m^3), respectively when compared with the same period in 2019 (Selvam et al., 2020). In India megacities like Delhi, about 30% of PM is from road traffic while other sources include construction and industrial activities which were all suspended during the lockdown period thereby resulting in immediate decrease in PM below the permissible limit (Mahato et al., 2020). The study of Resmi et al. (2020) involving air PM data in Kerala, India indicated that aisde from PM reduction, the two peaks (07:00 – 10:00 hours and 19:00 – 22:00 hours) in PM variation observed prior to lockdown vanished during the enhanced lockdown period. This is primarily due to the significant reduction in vehicular emissions. However, relaxing of restrictions in Delhi caused the concentration of PM to slightly increase, confirming that the lockdown measures contributed to the improvement of air quality (Mahato et al., 2020). Sharma et al. (2020) argued that the reduction of pollutants in megacities in India was greatly due to the regional transport restrictions, and not just due to local restrictions alone.

On the other hand, Kerimray et al. (2020) demonstrated in their study involving Almaty, Kazakhstan that despite the road traffic restrictions during the lockdown, $PM_{2.5}$ concentrations still exceeded the WHO daily limit values (25 μg/m^3). This indicates that $PM_{2.5}$ in this city was primarily due to non-traffic-related sources such as coal-fired combined heat and power plants, household heating systems, garbage burning and bath houses (Kerimray et al., 2020). In the case of the USA, $PM_{2.5}$ and PM_{10} decreased only in metropolitan cities where NO_2 declined the most (i.e. Northeastern US and California/Nevada area). Other areas with sources of PM other than traffic did not experience significant reduction in $PM_{2.5}$ and PM_{10} (Chen et al., 2020b). Meanwhile, Morales-Solís et al. (2021) also noted in all Chilean cities they studied that PM mostly come from residential sources primarily from burning of wood for heating purposes. Considering the above opposing findings on the changes in the PM levels in these places, it can be deduced that the PM reduction experienced by a city, region or country depended on whether its primary source of PM was halted by the COVID-19 lockdowns.

In Singapore, the 29% and 23% reduction in $PM_{2.5}$ and PM_{10} (relative to previous years), respectively, was correlated with mobility data (Li and Tartarini, 2020). Specifically, Google mobility data indicate that visit to transit stations and workplaces have the highest correlation coefficient, implying that restrictions in these industries contributed to the reduction in PM. It was also noted that among the areas considered in Singapore, the Southern and Western areas experienced the most reduction since these areas contain more heavy industries including the harbor and the airport. This implies that the reduction in the pollutants in different areas in a city may also be influenced by the spatial distribution of different pollution sources.

Contrary to the above observations, the PM levels in Ontario, Canada did not significantly change (Adams, 2020). This is due to the large contribution (56%) of residential sources to $PM_{2.5}$ emission, as compared to that of highways and street canyon (42%). Since the time spent in residential areas during the lockdown increased by 28%, its emission may have offset the reductions obtained from restricting transportation (Adams, 2020). Similalry, Pei et al. (2020) noted no change or even increase in $PM_{2.5}$ levels in Beijing, in contrast to other studies involving China which reported decrease in $PM_{2.5}$ (Chen et al., 2020a, Zheng et al., 2020). It was then noted that the behaviour of $PM_{2.5}$ concentration in China was geographically-dependent, with other major cities like Wuhan experiencing decrease while Guangzhou had steady levels of $PM_{2.5}$ (Pei et al., 2020). Moreover, Reddington et al. (2019) and Menut et al. (2020) noted that residential areas in China and Western Europe, contribute significantly to $PM_{2.5}$, hence it is likely that increased time spent in these areas may have contributed to the increase during the lockdown periods. Similarly, in

Southwestern China, the $PM_{2.5}$ increased by 24% relative to the same period in 2019 concluding that the lockdown was not effective in improving air quality (Chen et al., 2020c).

Meanwhile, in Baghdad, Iraq, $PM_{2.5}$ and PM_{10} decreased on the initial phase of the lockdown but eventually increased above the WHO limit (25 µg/m^3 for $PM_{2.5}$ and 50 µg/m^3 for PM_{10}) at the latter part of the lockdown period (i.e. end of April 2021). This period corresponds to summer in Iraq when dust is raised to the atmosphere by wind movement, adding to the transportation and industrial activities as source of PM (Hashim et al., 2021). Similarly, in London, $PM_{2.5}$ and PM_{10} increased after the lockdown due to long-range transport driven by anticyclonic eastely flows (Environmental Research Group King's College London, 2020).

These findings revealed that the restrictions in transportation and other industries during the lockdown periods may only minimally and temporarily change the level of PM, as these pollutants may also come from other sources, specifically residential areas as well as through secondary formation in the atmosphere. Specifically, in the study of Zheng et al. (2020), it was shown that the changes in the chemical composition of $PM_{2.5}$ was associated with the reduction in primary emission but increased in secondary formation. Moreover, the reduction in PM concentration was not sustained and its concentration eventually increased again as restrictions were eased. In addition, PM concentration in an area was also affected by long-range transport of pollutants which adds complexity in the analysis of pollution reduction due to lockdowns.

4.1.2 Nitrogen Dioxide (NO_2)

Elevated concentration of nitrous oxide (NOx) is typically observed in densely populated urban areas (Naethe et al., 2020). It is usually emitted from industries that involve high temperature combustion of fossil fuels, automobile and shipping industries (Tobías et al., 2020). Therefore, it is commonly used as an indicator of the level of air pollution and industrial activity in an area (Otmani et al., 2020). One component of NOx that plays an important role in the formation of O_3, secondary aerosol production and acid deposition is NO_2 (Cui et al., 2019). In most studies reviewed in this paper, NO_2 showed the largest change among the pollutants and was therefore used as the indicator whether air quality improvement was achieved during the lockdown periods (Anil and Alagha, 2020, Kumari and Toshniwal, 2020b, Menut et al., 2020, Silver et al., 2020, Liu et al., 2021, Islam and Chowdhury, 2021).

Like other pollutants, many studies show that the NO_2 concentration in the air was decreased during the lockdown periods as compared to pre-lockdown data and similar periods in the previous years (Dhaka et al., 2020, Kerimray et al., 2020, Mahato et al., 2020, Otmani et al., 2020, Resmi et al., 2020, Selvam et al., 2020, Zambrano-Monserrate and Ruano, 2020). In Western India, for example, the NO_2 content in the air was decreased by 30 – 84% relative to the pre-lockdown period (Selvam et al., 2020) while in East China, it decreased by 30% relative to the same period in 2019 (Filonchyk et al., 2020). In Quito, Ecuador, Zambrano-Monserrate and Ruano (2020) observed reduction in NO_2 by up to 5.8 times as compared to the past 2 years. In Indo-Pak (India-Pakistan) region, about 40-50% reduction in NO_2 emission was observed in its major cities like Lahore and Chennai (Arshad et al., 2020). Across Europe, particularly Spain, France and Italy, NO_2 was also reduced by up to 50% as compared to 2015-2019 data (Ordóñez et al., 2020). In Southeast Asia, particularly in the urban and industrial centers of Malaysia, reduction in NO_2 was up to 60% (Kanniah et al., 2020).

Similar to the decreasing trend of $PM_{2.5}$ in Singapore, the reduction in NO_2 was also correlated with the mobility data as both of these pollutants have the same origins, although NO_2 is more traffic-related than $PM_{2.5}$ (Li and Tartarini, 2020, Wang et al., 2020a). Specifically, the NO_2 reduction in Singapore was associated with the mobility restrictions in the aviation, refining and harbor activities (Li and Tartarini, 2020) which agrees with the conclusion of Venter et al. (2020) that the reduction in the emission from the transport sector was the primary reason for the NO_2 reduction in 34 countries across the globe. Aside from reduction in vehicle emission, decrease in NO_2 was also associated with the lesser emission from other industries during the lockdown period (Mor et al., 2021, Pei et al., 2020, Selvam et al., 2020, Silver et al., 2020). Among the studies reviewed, only that of Wetchayont (2021) in Bangkok, Thailand reported up to 27% increase in NO_2 and was related to increased biomass burning as well as a forest fire in Northern Thailand.

The study of Chen et al. (2020b) which monitored the NO_2 reduction across the USA highlighted the influence of population density on the changes in NO_2 levels during the lockdowns. Generally, NO_2 reduction is higher in areas with higher population density (>4000 per square mile). The same trend was observed by Jephcote et al. (2021) in their study concerning United Kingdom, where higher reduction in NO_2 was observed in more urban traffic sites than in suburban and rural areas.

Although reduction in NO_x may be beneficial as it reduces the risk of NOx-related health problems (Arshad et al., 2020), it contributes to the increase in O_3 production (Sec 4.1.4). This adds complexity to the chemistry and potential interaction of atmospheric pollutants that have to be understood in formulating sustainable air pollution control strategies.

Similar to what was observed with other pollutants, the level of NO_2 in most cities and countries either normalized or increased after the lifting of the lockdown restrictions. For example, in Wuhan province and in European countries like Italy, Spain and United Kingdom, NO_2 returned to its pre-lockdown levels as early as the lifting of the lockdowns (Venter et al., 2020).

4.1.3 Sulfur Dioxide (SO_2)

Although SO_2 may be released to the atmosphere through natural emissions like volcanic eruption, its major anthropogenic source include combustion of sulfur-containing fuels (i.e. coal and diesel) (Smith et al., 2001). SO_2 reduction of up to 50% relative to the pre-lockdown period was recorded in Sale City (Morocco) as the city implemented strict lockdown measures (Otmani et al., 2020). In China where SO_2 level has already been reduced for the past years (Silver et al., 2020), no significant reduction was observed during the lockdown (Pei et al., 2020). This low SO_2 level in China is due to its effort to transition from coal to cleaner energy source (He et al., 2020a). No significant change in SO_2 level was also observed in Milan, Italy during the lockdowns (Collivignarelli et al., 2020) while only 8 – 30% reduction was observed in the Eastern Province, Saudi Arabia due to the relatively low emission of SO_2 in these areas even before the lockdown (Anil and Alagha, 2020).

Otmani et al. (2020) and Selvam et al. (2020) particularly identified the reduction in shipping and fishing activities to be a major contributor to the decrease in SO_2 by 40 % (22 $\mu g/m^3$) in Gujarat State, India and 50% (3.2 $\mu g/m^3$) in Sale City (Morocco). This is supported by Mahato et al. (2020) who indicated that Delhi usually obtain SO_2 level that is below the acceptable limit even before lockdown due to its distance from the harbors.

On the other hand, SO_2 level observed by Mor et al. (2021) in Chandigarh, India showed a continuous increase as the three-phase lockdown progressed. It increased by up to almost 20% relative to the pre-lockdown value. This increase was attributed to the atmospheric transportation of SO_2 from coal power plants in the neighboring states around Chandigarh, which remained operational during the lockdown period (Mor et al., 2021). Similarly, in Sigrauli, India where there is the country's largest coal power plant (Vindhyalchal Super Thermal Power) that continued its operation even during the lockdown, SO_2 concentration was higher during the lockdown than the pre-lockdown periods (Kumari and Toshniwal, 2020a). Across United Kingodm, the SO_2 in the atmosphere during the lockdown period increased to more than twice the value in 2019 and 7- year average (Higham et al., 2020). This increase in SO_2 was unlikely to be from primary emissions and therefore may be due to meteorological factors such as less rainfall and low relative humidity which then decrease SO_2 sink (Higham et al., 2020). Similarly, the study of Wetchayont (2021) reported up to 85% increase in SO_2 in Bangkok, Thailand. However, the study could not determine the specific industrial emission source which may have caused such huge increase.

In summary, the SO_2 emission generally decreased during the lockdown period due to the reduction in SO_2-emitting activities. However, some areas experienced increase in SO_2 potentially due to long-range transport and the influence of meteorological factors. This again highlights the involvement of other factors that influence the reduction of pollutants in the atmosphere, other than the usual intentional reduction at source.

4.1.4 Ground-level Ozone (O_3)

Unlike other pollutants which showed reduction in concentration during the lockdown periods, ground-level O_3 concentration increased in most cities and regions (Anil and Alagha, 2020, Kerimray et al., 2020, Hashim et al., 2021, Sharma et al., 2020). In general, the concentration of O_3 is a function of the magnitude and ratio of the emission of precursor gases such as NO_x and VOCs, the intensity of photochemical reactions, atmospheric conditions, and local and regional factors that influence removal processes at the Earth's surface (Dentener et al., 2020, Sitaras and Siskos, 2008). Specifically, the increase in O_3 to up to twice the levels in 2018 – 2019 noted by different studies (Selvam et al., 2020, Zambrano-Monserrate and Ruano, 2020, Zheng et al., 2020) (Table 1) is potentially due to the decrease in $PM_{2.5}$ which consumes hydroxyperoxyl radicals. These hydroxyperoxyl radicals normally react with nitric oxide (NO) to produce O_3 (Li et al., 2019), therefore reduction in PM results in more available hydroxyperoxyl radicals for O_3 formation. Specifically, PM reduction improves the intensity of solar radiation, increases air temperature and reduces relative humidity which all contributed to O_3 generation (Resmi et al., 2020, Zambrano-Monserrate and Ruano, 2020).

The reduction of NOx brought about by lockdown measures may have also contributed to the increase of O_3 (Selvam et al., 2020, Sharma et al., 2020, Nigam et al., 2021). Hernández-Paniagua et al. (2021) noted 16-40% increase in O_3 in the same sites in Mexico City Metropolitan Area where NO_2 reduction of 10-43% was observed. Reduction in NOx, specifically NO_2, increases secondary organic aerosol and decreases nitrate (Chen et al., 2020a). This leads to less consumption of O_3 during titration (i.e. $NO + O_3 = NO_2 + O_2$) (Mahato et al., 2020, Selvam et al., 2020, Pei et al., 2020). Among the studies which monitored O_3 during the COVID-19 lockdowns, that of Wetchayont (2021) in Bangkok, Thailand, reported decrease in O_3 which was explained to be due to the increase in NO_2 concentrations. This further supports the discussion above.

Apart from reduction in NOx, the decreased VOC emissions due to the significant reduction in fuel consumption by motor vehicles may also result in increments in O_3 level (Hernández-Paniagua et al., 2021). Finlayson-Pitts and Pitts (2000) explained that reduction in NOx results in an increase in OH radicals which subsequently react with the VOCs, promoting the production of O_3. The reduction in VOC levels also contribute to increase in O_3 level (Hernández-Paniagua et al., 2021), however it is not regularly monitored like other pollutants (Jephcote et al., 2021). Hence, Adam et al. (2021) illustrated in their review paper that O_3 production rate is strongly influenced by the high VOC/NO_x ratio that resulted from reduction in NO_x. Moreover, Dhaka et al. (2020), Mor et al. (2021), Resmi et al. (2020) and Sharma et al. (2020) added that along with the reduction in NO_2 and VOCs, the increased solar radiation during the lockdown period also contribute to the increase of ozone as it enhances photochemical reactions with these gases. This again highlights the need to understand the interaction between pollutants and meteorological factors in crafting policies related to air quality improvement.

The influence of meteorological factors in O_3 generation is highlighted in the reduced O_3 levels in Iberian Peninsula in Europe as observed by Ordóñez et al. (2020). In particular, the lower solar radiation and higher specific humidity in this region as compared to the northwestern and central regions of Europe contributed to its reduced O_3 levels. Moreover, O_3 has an atmospheric lifetime of several weeks and its level is therefore prone to the effects of long-distance transport associated with meteorological patterns (Venter et al., 2020). This emphasizes the need to consider meteorology and the extent to which it influences air pollution.

In conclusion, the increase in O_3 levels despite reduction in primary emissions during the lockdown periods showed that controlling its formation is a challenging task and requires a better understanding and control of the chemistry involved. Akimoto et al. (2015) suggested an integrated air pollution control policy which necessitates the simultaneous reduction of NO_x and VOCs emissions which are precursors to O_3 and secondary aerosol ($PM_{2.5}$) formation. This is the co-mitigation of PM and O_3 recommended by Adam et al. (2021) as among the pollution control policies that can be advocated by policy makers.

4.1.5 Carbon Monoxide (CO)

CO is often used as an indicator of primary emission due to its relatively long lifetime against oxidation in the atmosphere (DeCarlo et al., 2010). Similar to NO_2, CO is also emitted primarily from automobiles, manufacturing industry and power plants, hence lockdowns expectedly decrease its emission. This decrease in CO was noted in many studies (Collivignarelli et al., 2020, Li and Tartarini, 2020, Mahato et al., 2020, Mor et al., 2021, Resmi et al., 2020, Selvam et al., 2020). On the contrary, despite the reduction in road traffic in Mexico City Metropolitan Area, CO levels did not significantly decrease potentially due to the increase CO emission from other sources such as the increased domestic use of liquid petroleum and natural gas because of the stay-home order from the government (Hernández-Paniagua et al., 2021).

In Chandigarh, India, the percent reduction in CO relative to the pre-lockdown period was up to 17% and decreased to only 3% when the restrictions were relaxed as the lockdown progressed (Mor et al., 2021). This was potentially due to the increase in vehicular and industry emissions which gradually returned with the relaxation of lockdown measures. The reduction of vehicular traffic in Milan, Italy was also identified as the major cause of CO reduction during the lockdown (Collivignarelli et al., 2020).

Unlike other major pollutants discussed above, changes in CO was not widely monitored in the studies reviewed in this paper. Hence, the limited information. Nevertheless, it is evident that since its primary sources are similar to that of NO_2, its concentration also decreased due to the restrictions imposed by the COVID-19 lockdowns.

5. Overall Implications

5.1 Influence of Meteorological Factors

Although the influence of meteorology on the improvement of air quality during the lockdown periods was not considered in most of the studies discussed above, the large difference in the air quality during this period and in the previous years may be adequate to conclude that such improvement was due to the lockdown measures (Adams, 2020, Kerimray et al., 2020, Zambrano-Monserrate and Ruano, 2020). Pei et al. (2020) and Zheng et al. (2020) observed that the contribution of meteorology in the air quality improvement in Chinese cities was only secondary. However, Ordóñez et al. (2020) highlighted the importance of meteorology in explaining discrepancies in ozone production and emission changes during the lockdown period in Europe. Similarly, Chauhan and Singh (2020) emphasized the contribution of rainfall to the reduction of $PM_{2.5}$ in New York and Los Angeles, relative to 2019 and pre-lockdown data. Although the study of Wu et al. (2021) focused on atmospheric mercury concentrations and not on the five major pollutants discussed above, it was observed that enhanced relative humidity and temperature during the COVID-19 lockdowns significantly offset the emission reduction effect of the lockdowns. This means that if favorable meteorological conditions were present, higher reduction in atmospheric mercury could have been observed. Moreover, Hernández-Paniagua et al. (2021) estimated that changes in air quality may be overestimated by up to 10-fold if meteorological factors are disregarded. Hence, to eliminate the potential influence of meteorology in their analysis, days with stagnant and heavy precipitation were excluded. Hence, meteorological conditions and factors should be carefully considered in quantifying the changes in air quality brought about by the lockdowns.

Shen et al. (2021) observed and modeled that long-range transport of air pollutants from Central East China contributed to about 50% to the $PM_{2.5}$ pollution in the Hubei province in Central China. Long-range transport from polluted upwind regions also contributed to the increase in SO_2 concentration (relative to 2019 data) in Seoul and Tokyo metropolitan areas as observed by (Ghahremanloo et al., 2021). Additionally, Islam and Chowdhury (2021) hypothesized that the lesser improvement of air quality in Dhaka, Bangladesh as compared to other cities in the world may have been due to movement of air pollutants from neighboring regions or cities (i.e. Kolkata, Pakistan and Nepal). These observations highlight the significance of meteorology in influencing the regional air quality in China. On the other hand, after weather normalization technique done by Zheng et al. (2020) on data pertaining to Wuhan, China, the improvement in air quality in terms of $PM_{2.5}$ reduction was determined to be predominantly due to emission reduction (92%) with meteorology contributing to only 8% of the $PM_{2.5}$ reduction. Moreover, long-range transport of pollutants and its contribution to air quality in a specific area highlights the need for international cooperation on global air quality improvement initiatives.

5.2 Factors Affecting the Extent of Pollution Reduction

In most studies, the decrease in the pollutants and the improvement in air quality were more pronounced during the phases of the lockdowns when restrictions were tighter than those phases where restrictions started to relax (Mor et al., 2021, Sharma et al., 2020, Kumari and Toshniwal, 2020a, Nigam et al., 2021, Hernández-Paniagua et al., 2021, Stratoulias and Nuthammachot, 2020). Specifically, (Kumari and Toshniwal, 2020a) observed that concentration of $PM_{2.5}$, PM_{10}, SO_2 and O_3 in Indian cities started increasing upon the cessation of lockdown measures. Wetchayont (2021) observed the same for Greater Bangkok in Thailand where all major pollutants except O_3 increased after the restrictions were lifted. Moreover, the air quality in Singrauli, India where the largest thermal power station is situated and remained operational during the lockdown, demonstrated the least pronounced improvement as compared to Delhi and Mumbai which both implemented stringent lockdown measures (Kumari and Toshniwal, 2020a). Similarly, Silver et al. (2020) and Dang and Trinh (2020) noted that the observed improvement in air quality in China and in Vietnam, respectively, returned to their pre-lockdown levels after the lifting of restrictions. Moreover, the comparison between Chinese cities with and without stringent lockdown policies indicated that lockdown indeed improved air quality indices by up to 26 points (He et al., 2020b). Hence, many of these studies safely concluded that the restriction of anthropogenic activities which resulted from the lockdown measures significantly contributed to the improvement in the air quality (Dang and Trinh, 2020, Ghosh et al., 2020, He et al., 2020b, Sharma et al., 2020). Hence, such measures may constitute as an alternative solution in minimizing environmental degradation (Ghosh et al., 2020, Kumari and Toshniwal, 2020a, Mahato et al., 2020). On the contrary, Pei et al. (2020) concluded its inadequacy as a control measure and emphasized the need for a more comprehensive and synergistic control of atmospheric pollutants, particularly VOCs. Moreover, He et al. (2020b) argued that the economic cost of implementing total lockdown makes it an impractical and unsustainable air pollution control measure and suggested alternatives that are more economically feasible such as stricter gasoline fuel standards and the Two Control Zone policy, among others.

It is also noteworthy that the reduction in air pollution and improvement in air quality was greater in more populated and industrialized cities/areas as observed by Selvam et al. (2020) in Gujarat, India, He et al. (2020b) in Chinese cities and Ordóñez et al. (2020) in Europe and Jephcote et al. (2021) in United Kingdom. This was also observed by the Environmental Research Group King's College London (2020) where NO_2 reduction was lower in remote roads and urban background sites than in urban centers and busier roads. The comparison between the two cities of Ankleshwar and Vapi in Gujarat, India highlighted the influence of the level of industrial activities and the proximity to the coast, on the emission trends (Nigam et al., 2021). Similarly, Hernández-Paniagua et al. (2021) observed in Mexico City Metropolitan Area that significant SO_2 reduction was observed only in sites with heavy-duty vehicles and buses. These observations confirm that anthropogenic activities are indeed major sources of pollutant emissions which when reduced can improve air quality. Moreover, due to the increased time spent in residential areas (Adams, 2020), residential sources of pollutants may have a significant impact on the air quality during the lockdown similar to what was observed in Chandigarh, India (Mor et al., 2021). In addition, the study of Wetchayont (2021) and Jephcote et al. (2021) which demonstrated that urban traffic is just one of the sources of pollutants, indicate that a sustainable improvement in quality can be achieved through policies that encompass sectors and emission sources other than transportation.

It is interesting to note that Liu et al. (2021) who examined air pollution data from 76 countries during the lockdown periods observed that larger reduction in air pollution was observed in cities from lower-income and larger-population countries. It was argued that most high-income countries generally have lower level of air pollution even before the lockdowns and therefore have smaller room for further reduction. Liu et al. (2021) further demonstrated that industrial activities are major sources of air pollutants as reduction in air pollution level was more significant in cities with more industrial activities.

5.3 Impact of Pollution Reduction to Health

Although many studies have demonstrated the potential of restrictions similar to COVID-19 lockdowns in reducing air pollution levels, only a few studies specifically correlated the improvement in air quality brought about by lockdown measures to reduction in air pollution-related morbidity. Miyazaki et al. (2020) estimated that during the lockdown periods in China, at least 60,000 reduction in $PM_{2.5}$-realted illness could be observed due to reduction in $PM_{2.5}$ while approximately additional 2,100 ozone-related health cases with increased O_3 levels in most Chinese cities. Additionally, Hernández-Paniagua et al. (2021) calculated the potential health benefits of air quality changes during the COVID-19 lockdowns and suggested that approximately 600 deaths were prevented due to reduction in exposure to outdoor air pollutants. In a bigger study conducted by Liu et al. (2021) involving 76 countries and regions (597 major cities), it was estimated that up to 150,000 premature deaths could be prevented by improvement in air quality (i.e. only in terms of $PM_{2.5}$ reduction). Moreover, the potential benefit of decreasing COVID-19 transmission with the improvement of air quality is also mentioned (Resmi et al., 2020) and warrant further studies.

To further strengthen the observation that lockdown measures can considerably reduce air pollution and be a promising solution to environmental restoration, the influence of long-range transport of PM and other gases must also be investigated (Miyazaki et al., 2020, Otmani et al., 2020). This kind of correlation was demonstrated in the work of Griffith et al. (2020) which showed that reduced emission in mainland China contributed to approximately 50% reduction in $PM_{2.5}$ in Taiwan Province. Similarly, Mor et al. (2021) also noted this long-range transport of pollutants as secondary source of pollution in an area, as observed for SO_2 data in Chandigarh, India (Sec 4.1.3) and for PM and O_3 data in London (Sec 4.1.4) (Environmental Research Group King's College London, 2020). Understanding the influence of long-range pollutant transport is important as it emphasizes the need for cooperation among countries and regions to work together in achieving emission targets set by WHO.

6. Conclusions

Overall, most of the studies reviewed concluded that the changes in the air quality during the lockdown period was primarily due to the reduction in emissions for various sector but meteorological variables that influence long-range transport of pollutants and non-linear response of secondary pollutant formation to the reduction of precursor pollutants cannot be ignored and requires further investigation.

The results of these studies further ascertain how anthropocentric activities influence the level of pollution in an area and that dramatic reduction in these activities also results in short-term air quality improvement. Nevertheless, an effective and sustainable pollution-reduction program requires global cooperation and considers meteorological factors. Moreover, social, cultural and economic consideration shall also be estimated and evaluated by policy makers in crafting policies relevant to sustainable reduction and/or control of global air pollution.

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