CHAPTER EIGHT

Air quality during COVID-19 lockdown and its implication toward sustainable development goals

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1. Introduction

Governments of the various nations across the globe had to unwillingly shut down their nonessential economic activities by declaring lockdown as an initial preventive measure to tackle the novel coronavirus (COVID-19). It has impacted millions of lives, but this number could have been worst without the lockdown. Highly populated countries such as China and India have implemented the longest lockdown spanning more than six weeks.[1,2] Almost every country has implemented lockdown as their first response to the COVID-19 pandemic in order to lower the spread rate and develop the necessary health infrastructure to deal with the cases. Further, additional measures such as social distancing, lockdowns, stay-at-home orders, and mandatory use of masks in public places have been implemented by all the countries to reduce the spread of the disease.[3] Air-conditioned restaurants, malls, theaters, and institutions remained closed as these places are considered to be potential spreaders. Public gatherings and religious events are banned over most of the regions, besides weddings and funerals are allowed with a very limited number of attendees.[4] Nonessential small industries; information technology firms; and the air, rail, and road transport sector also stopped their operations during the lockdown. As a result, these measures led to a decline in air pollutants and greenhouse gas (GHG)

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emissions and thus air quality improvement around the world.[5,6] However, this has also shown our vulnerability toward the global crisis forcing the governments as well as the scientific community to rethink our pace and choices toward sustainable life.[7]

Several studies across the world have quantified the significant decline in the concentrations of different air pollutants during the lockdown.[1,6,8–15] Primary air pollutants, such as $PM_{2.5}$, PM_{10}, NO_2, and CO which are largely associated with vehicular emissions in urban areas, have observed the highest decline (>50%) across all regions, with a higher decline in more polluted cities. One of the key regions in the air pollution study, the Indo-Gangetic Plain (IGP), reported air quality below the permissible limits after many decades.[1]

Aerosols remained the highly discussed topic during the pandemic for their involvement in the spread of the virus, as evidences showed, not just the physical contact but droplets from coughing/sneezing and inhalation of small airborne particles can transmit from an infected to an uninfected person.[16] A two-meter distance protocol only works when the mask is on; otherwise, even 6 m may not be enough to avoid the spread of the virus.[17] Although engineering controls can prevent the spread,[18] but studies have strongly suggested about airborne transmission route of COVID-19 as well.[19] On the other hand, long-term exposure to bad air quality may increase the vulnerability of people with preexisting and compromised lung conditions.[20,21] It has been reported that regions with higher $PM_{2.5}$ could potentially result in threefold higher mortality.[22] Similar risk associations have also reported during the SARS pandemic in 2003.[23]

A few epidemiological studies have examined the environmental conditions which could affect the spread of the virus, primarily examining the association of temperature and relative humidity with daily new cases.[24–26] However, the role of meteorology on air quality vis-à-vis the effect of lockdown has been quantified by a handful of studies only.[1,27]

All of these choices during the lockdown affect our commitment toward 17 SDGs (169 SDGs-related targets) decided by the United Nations (UN) under the *Transforming Our World: The 2030* agenda in 2015.[28] Air pollution and GHGs are considered as one of the significant indicators to monitor the progress of four SDGs, which include SDG3 (Good health and well-being), SDG7 (Clean energy), SDG11 (Sustainable cities), and SDG13 (Climate actions).[28,29] Two of the SDG targets explicitly highlight the importance of air pollution: SDG 3.9 targets a substantial reduction in the number of deaths and illnesses from hazardous chemicals and air, water, and soil pollution and contamination by 2030, while SDG 11.6 targets reduction in the adverse per capita environmental impact of cities, including by paying special attention to air quality, municipal and other waste management.[28,30] The complexity to understand the consequences of SDG-related decisions is somewhat seen during the pandemic and exploitation of the available data can help in future policy-making.

Thus, to understand future measures to improve air quality and mitigate the adverse health and climate effects, it is necessary to exploit the current scenario. This chapter explores the impact of the national lockdowns on urban air quality across the globe and discusses future policy implications toward improving air quality from the learnings of this natural intervention.

2. Lockdown measures adopted around the world

Affecting more than 200 countries as of Sep 07, 2020,[31] the pandemic has forced every country to restrict their internal as well as external movements. Activities were only allowed locally based on the absolute essentials so that this restriction (also known as lockdown, stay-at-home, curfews, or shutdown) could reasonably reduce the spread of the virus at the initial stage and provide the governments a time window to establish and expand required health facilities. Countries such as Italy, India, China, and Mexico have declared some of the largest lockdowns in history (see Table 1). India

Table 1 Lockdown details of 20 worst-affected countries.

Sr. No.	Country	Start	End	Level	Reference
1	USA	19-Mar	11 May	Regional	32,33
2	India	25-Mar	07-Jun	National	34
3	Brazil	24-Mar	10-May	State	35
4	Russia	28-Mar	30-Apr	National	36
5	Peru	16-Mar	30-Jun	National	37
6	Colombia	6-Apr	15-Jul	National	38
7	South Africa	26-Mar	30-Apr	National	39,40
8	Mexico	23-Mar	01-Jun	National	41
9	Spain	14-Mar	09-May	National	42
10	Argentina	20-Mar	28-Jun	National	43
11	Chile	29-Jul	17-Aug	City	44
12	Iran	14-Mar	20-Apr	National	45,46
13	UK	23-Mar	30-Jun	National	27
14	Bangladesh	26-Mar	30-May	National	47

Continued

Table 1 Lockdown details of 20 worst-affected countries—cont'd

Sr. No.	Country	Start	End	Level	Reference
15	France	17-Mar	11-May	National	48
16	Saudi Arabia	23-Mar	20-Jun	National	49
17	Pakistan	24-Mar	09-May	National	50
18	Turkey	23-Apr	27-Apr	Cities	51
19	Italy	09-Mar	18-May	National	52
20	Iraq	22-Mar	11-Apr	National	53,54

USA: ~28 states declared regional lockdown; **India:** Some states have extended the lockdown; **Brazil:** São Paulo only declared lockdown; **Russia:** lockdown extended for Moscow till 12–05; **Chile:** 3 Metro areas, Nighttime curfew 22:00–06:00; **Bangladesh:** Nighttime curfew 20:00–06:00; **Turkey:** Major 31 Metro areas gone through lockdown; **Italy:** lockdown Started from Northern Italy.

recorded the biggest lockdown ever by restricting more than 1.3 billion population voluntarily in a house for "*Janta Curfew*" on March 22, 2020,[55] followed by six-week long strict lockdown across the country.[1] However, the length of the lockdown does not represent the effective prevention of the virus spread. Some countries such as South Korea and Sweden haven't introduced any lockdown during the pandemic,[56] while countries such as Brazil[35] implemented the lockdown in major cities and high-risk areas only. Chile[57] and Bangladesh[58] have also tried nighttime curfew to limit nocturnal movements (see Table 1). These lockdowns are implemented phase-wise to have a timely evaluation of the situation while considering the revival of economic activities.

Oxford COVID-19 Government Response Tracker (OxCGRT) is continuously monitoring the government policies of 180 different countries and classifying the publicly available information into 17 indicators which are further summed into four groups indicating health, economic, policy information, and overall effect.[59] Fig. 1, compiled from the OxCGRT, shows the stringency index of each country for the government policies, which is derived from the orders such as closure or restriction of school, workspace, public event, social gathering, public transport, internal movement, and international travel.[59] The majority of the strict protocols by various countries have been enforced between 15th March and 15th April and followed up to June 2020. Thus the period of April–May remained the most restricted months due to overlapping lockdown orders from various governments (Fig. 2). China was the first country to declare nationwide lockdown and successfully prevented the spread of the virus in Wuhan using early lockdown and exhaustive testing.[60] India expected to be the worst affected country, with the longest lockdown enforced by some of the state governments even after the reopening order from the central government.[61]

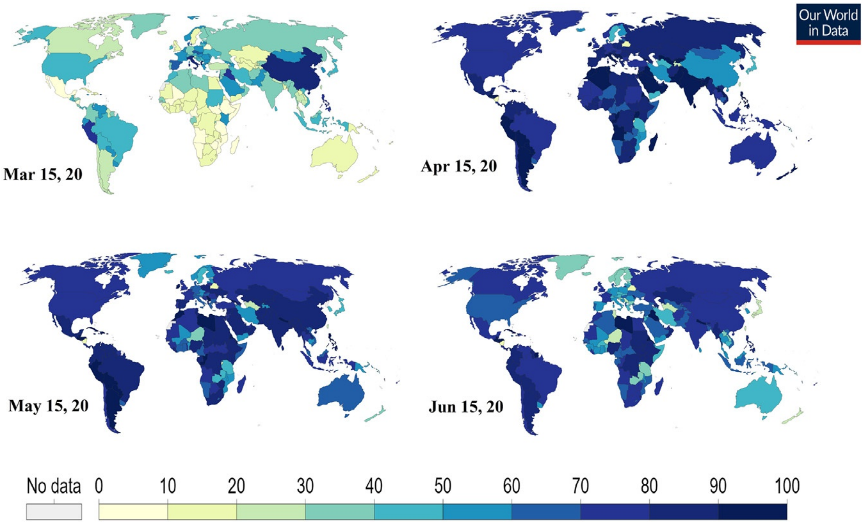

Fig. 1 COVID-19: Government response stringency index. As of Sep 07, 2020.[59] (This is a composite measure based on nine response indicators, including school closure, workplace closure, and travel bans, rescaled to a value from 0 to 100 (100 = strictest). The index simply records the number and strictness of government policies and should not be interpreted as "scoring" the appropriateness or effectiveness of a country's response. OurWorldInData.org/coronavirus CC BY.)

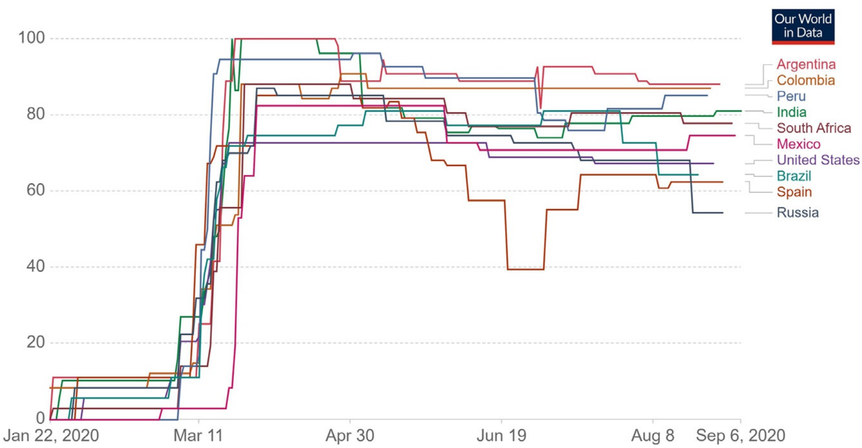

Fig. 2 Change in government response stringency index with the time for the top ten worst-affected countries. As of Sep 07, 2020.[59] (This is a composite measure based on nine response indicators, including school closure, workplace closure, and travel bans, rescaled to a value from 0 to 100 (100 = strictest). The index simply records the number and strictness of government policies and should not be interpreted as "scoring" the appropriateness or effectiveness of a country's response. OurWorldInData.org/coronavirus CC BY.)

Despite strict lockdown orders in many developing countries, the daily surge of new COVID-19 cases showed unconstrained growth.[62] Some studies have examined the effectiveness of these lockdowns by analyzing variability in the daily new cases, using various tools such as Growth Factor,[63] Daily Incidence Proportion, Daily Cumulative Index,[64] and Effective Reproduction Number.[65] These studies show that the lockdown in countries like Bangladesh, Brazil, Chile, Pakistan, and South Africa has failed to control the situation, where unbridled daily new cases have been observed during lockdown.[62] The effectiveness of the lockdown in the aforementioned developing countries also depends on the behavior of the citizens to understand the importance of social distancing and successful confinement of the key cities to prevent rural areas from getting infected. The economy of the developing countries heavily relies on the metropolitan cities, which in some way impacted the effectiveness of the lockdown, and virus infection spread to rural regions as most of the daily wage workers migrated to their hometowns due to unemployment. The prolonged lockdown with rising daily new cases can have socioeconomic consequences, while this unprecedented disruption in the major economic activities can ignite many issues such as unemployment.[66]

3. Air quality during COVID-19 lockdown

The economic growth of many developed and rapidly developing nations has aggravated air pollution levels, specifically in urban areas. Worsening air quality in many parts of the world is a severe threat to the human respiratory system considering the long-term exposure to the criteria air pollutants ($PM_{2.5}$, PM_{10}, NO_2, SO_2, CO, and O_3).[67–70] More than ~5 million deaths are annually attributed to air pollution.[71] These emissions are mainly due to vehicular, agriculture, residential, and industrial (including power) sectors.[72–76] These sources have been operating uninterrupted for many decades which has gradually degraded the air quality, but worldwide the lockdown due to the COVID-19 virus outbreak can be considered as the biggest hiatus for human activities and thus the emissions from these sources during the modern era.[77]

The unrestrained spread of COVID-19 with no vaccine available as of Sep 2020 forced everyone to stay indoors and the economic activities went down. As a consequence, the imposed lockdowns have provided a unique opportunity to examine the earth's atmosphere without the emissions from major sectors.[77,78] Thus this natural intervention across the globe presented a unique opportunity for the scientific community leading to numerous studies recording a marked decline in air pollution levels during the COVID-19 lockdown.

A majority of these studies are from India[1,8,9,12,79] and China.[80–84] The air quality impact of the lockdown has also been investigated in the USA,[85] Brazil,[10] Malaysia,[13,86] Spain,[11] Pakistan,[87] Kazakhstan,[88] Iran,[89] Tehran,[90] Ecuador,[91] Istanbul,[92] and UK[27,93] as well. The global decline in pollutants considering a common lockdown period is also analyzed by a few studies[6,94] and found a similar range of pollutant changes as observed by the regional or city/country-specific studies.

3.1 Change in air quality during lockdown

3.1.1 Asia

In the past few decades, (Indo-Gangetic Plain) IGP (India),[95] Beijing (China),[96] and Lahore (Pakistan)[97] are in discussion for their particulate pollution-related issues, owing to the aforementioned sectors along with some natural aerosols such as dust from long-range transport.

In Feb 2020, NASA had released the initial evidence showing the tropospheric NO_2 density $< 100\,\mu mol\,m^{-2}$ during the lockdown (Feb 10–25, 2020) in Wuhan, China; these values were fivefold lesser than the previous year.[98] Further, NASA released NO_2 and (Aerosol Optical Depth) AOD decline over the Indian region, clearly showing AOD reduction up to $\sim$0.5, especially over the IGP region.[98] Researchers show a significant reduction in the major criteria air pollutants which is due to the lockdown effect leading to the closure of nonessential sectors and decreased vehicular mobility on the road.[1,9,79]Kumar et al.[99] reported considerable reductions in $PM_{2.5}$ in 5 major cities of India compared to the same period of the previous 5 years, where it reduced to 41%–53% (Delhi), 10%–39% (Mumbai), 19%–43% (Chennai), 26%–54% (Hyderabad), and 24%–36% (Kolkata). Navinya et al.[1] also reported a significant decrease in postlockdown $PM_{2.5}$ and PM_{10} in 17 cities across India. Mahato et al.[79] reported a decrease of more than 50% in $PM_{2.5}$ and PM_{10} concentrations over Delhi, India. Mitra et al.[100] reported $PM_{2.5}$ (39%), PM_{10} (60%), CO (30%), and NO_2 (53%) reduction during lockdown compared to 2019 in Kolkata, India. Many of the studies have reported different estimations of air pollutant reduction in the same cities due to the variation in selection of the number of days, stations, lockdown periods, and control periods. Saadat et al.[101] reported a 25% decrease in emissions at the start of the lockdown based on Chinese emission data, as coal usage decreased by 40% due to the slowdown of factories and power plants. They further estimated 11% improvement in air quality during lockdown compared to 2019 data from 330 cities of China. Major cities in China—Shanghai, Beijing, Wuhan, and Guangzhou—experienced a reduction in $PM_{2.5}$ by 6.4, 9.2, 30.8, and 5.4 $\mu g\,m^{-3}$, respectively, during the lockdown.[102] Kanniah et al.[103] reported a decrease in tropospheric NO_2 column density (27%–34%) in most South-East Asian countries. $PM_{2.5}$ and PM_{10} showed 23%–32% and 26%–31% decrease in urban, while 20%–42% and 28%–39% in industrial areas, respectively, compared with 2018 and 2019. A similar decrease of 40%–70% has also been observed in the AOD over urban areas of Malaysia during Mar–Apr 2020.

Overall, Ahmedabad (68%), Beijing (79%), Bangalore (87%), Nagpur (91%), and Zhejiang (69%) show the largest reduction for $PM_{2.5}$, PM_{10}, NO_2, SO_2, and CO, respectively, while Baghdad (225%), Delhi (37%), and Singrauli (35%) show increase in the ozone levels during the lockdown in Asia (see Table 2).

3.1.2 North and South America

NASA confirmed a 30% decline in atmospheric NO_2 over Northeastern USA during the lockdown.[117] A group of studies (Table 2) suggests that San Jose (45.0%), Las Vegas (41%), and Los Angeles (41%) showed the larger decline in $PM_{2.5}$, while sharp PM_{10} decline was observed over Los Angeles (57%), Las Vegas (54%), and Fresno (54%). Similar to Asia, the American continents also show a huge reduction in the atmospheric NO_2, with states such as Alabama (89%), California (89%), and Louisiana (83%) reported relatively very high reduction.[85] Similarly, a prompt reduction was observed in SO_2 over Quito (69%), Louisiana (61%), and Las Vegas (49%). The increase in O_3 is relatively lesser than in Asia, with Salt Lake (25%), Providence (20%), and Toronto (17%) showing a slight increase in surface ozone during the lockdown (see Table 2).

3.1.3 Europe

The Sentinel-5P, a European satellite mapped NO_2 over France and nearby, confirmed a significant reduction over Milan, Paris, and Madrid.[118] Similarly, NO_2 reduced by 56% over Scotland, with Glasgow showing ~39% decline (see Table 3). Reduction in the $PM_{2.5}$ is also significant over Vienna (57%), Paris (53%), and Scotland (48%). The highest reduction has been observed over Vienna (−61%) for PM_{10}. Surprisingly, SO_2 over the UK shows a significant and consistent increase by 82%–206%,[27] whereas surface

Table 2 Air quality change over major cities.

Continent	Country	City	Base time	$PM_{2.5}$	PM_{10}	NO_2	SO_2	CO	O_3
Africa	Ethiopia	Addis Ababa[104]	Pre-L	−5.4					
	Nigeria	Kaduna[105,a]	2004–19			−3.0	10.5		1.9
	Nigeria	Lagos[105,a]	2004–19			−1.4	54.0		2.2
	South Africa	Dublin[94]	2019	−45.2	−44.3				
Asia	Bangladesh	Dhaka[106,a]	Pre-L			−69.0	−66.6	−5.7	2.6
	China	Beijing[107]	2019	−6.5	−79.1	−25.6	−42.6	−11.0	
	China	Chengdu[94]	2019					−29.1	
	China	Nanjing[94]	2019	−31.3	−31.8		−46.1	23.8	
	China	Shanghai[107]	2019	−26.6	−29.1	−43.8	−31.2	−18.2	
	China	Suzhou[108]	2017–19	−33.5	−19.0	−36.5	−67.1	−5.8	−0.1
	China	Wuhan[80]	2017–19	−44.0	−47.9	−54.	−29.9	−16.2	27.1
	India	Ahmedabad[1]	2019	−67.7		−67.5	−33.4	−36.5	
	India	Bangalore[1,94]	2019	−45.4	−48.9	−86.7	−80.5	−24.2	−10.6
	India	Chennai[1]	2019	−30.2		−36.3	−69.2	−23.7	
	India	Delhi[1,109]	2019/Pre-L	−58.1	−70.5	−79.2	−53.2	−30.2	37.4
	India	Hyderabad[1]	2019	−19.4	−31.9	−35.0	26.0	−26.1	
	India	Jaipur[1,110]	2019/Pre-L	−50.5	−48.1	−68.4	−8.9	−55.0	−25.0
	India	Kolkata[1,111]	2019	−23.5	−24.2	−55.9	45.6	14.8	6.3
	India	Lucknow[1]	2019	−51.5		8.1	167.4	−30.1	
	India	Mumbai[1,109]	2019/Pre-L	−0.9	−27.3	−57.9	46.9	−45.6	20.7
	India	Nagpur[1]	2019	−52.6	−52.6	−49.9	−90.6	−63.0	
	Iran	Tehran[89,a]	2019	10.5	−11.3	−13.0	−12.5	−13.0	3.0
	Iraq	Baghdad[112]	Pre-L	0.0	55.0	−8.0			225.0
	Israel	Jerusalem[94]	2019					465.2	

Continued

Table 2 Air quality change over major cities—cont'd

Continent	Country	City	Base time	$PM_{2.5}$	PM_{10}	NO_2	SO_2	CO	O_3
	Japan	Tokyo[94]	2019						31.9
	Kazakhstan	Almaty[88]	2018–19/Pre-L	−21.0		−35.0	7.0	−49.0	15.0
	Malaysia	Kuala Lumpur[113]	Pre-L	−32.1		−65.6	38.5	−32.1	
	Malaysia	Seremban[113]	Pre-L	−16.8		−61.1	25.2	−21.0	
	Mongolia	Ulaanbaatar[94]	2019	−25.6	−43.4				
	Saudi Arabia	Al Ahsa[49]	Pre-L		−57.0	−34.0	128.0	0.8	27.0
	Saudi Arabia	Dammam[49]	Pre-L		7.8	−12.0	35.0	2.2	−82.0
	Saudi Arabia	Qatif[49]	Pre-L		−70.0	−26.0	−25.0	−42.0	35.0
	Singapore	Singapore[114]	2016–19	−29.0	−23.0	−54.0	−52.0	−6.0	18.0
	South Korea	Seoul[94]	2019					−13.4	
	Taiwan	Taipei[94]	2019					24.3	
	Thailand	Bangkok[94]	2019						−28.5
	UAE	Abu Dhabi[94]	2019	−32.4					
Asia/Europe	Turkey	Istanbul[92]	Pre-L	−33.0	−37.5	−36.5	−51.5	−49.0	
Australia	Australia	Sydney[94]	2019	−35.1					
Europe	Austria	Vienna[94]	2019	−57.1	−60.7	−18.1			
	France	Paris[94]	2019	−53.2	−52.7	−33.1			
	Netherlands	Amsterdam[94]	2019	−47.5				−35.1	
	Norway	Oslo[94]	2019			−28.3			
	Poland	Warsaw[94]	2019		−45.9			28.1	
Europe	Scotland[115]	–	2019	−48.4		−55.8			
	Spain	Madrid[94]	2019			−33.3			26.9
	Switzerland	Bern[94]	2019			−27.0			
	UK	Birmingham[27]	2013–19	−10.0		−34.0	117.0		34.0
	UK	Glasgow[27]	2013–19	−12.0		−39.0	152.0		50.3

	UK	London[27]	2013–19	−9.0		−35.0	82.0		35.0
	UK	Manchester[27]	2013–19	−10.0		−32.0	114.0		32.0
N. America	Canada	Toronto[94]	2019						17.8
	USA	Alabama[107]	2019	−30.7			−88.7		
	USA	Boston[85]	2017–19	−23.0		−36.0		−22.0	8.0
	USA	California[107]	2019	−27.7	−19.9	−44.2	−88.7		
	USA	Florida[107]	2019	−33.7	−32.3	−35.4	−73.3	−4.7	
	USA	Fresno[85]	2017–19	−25.0	−54.0	−42.0		−31.0	−9.0
	USA	Las Vegas[85]	2017–19	−41.0	−55.0	−49.0		−28.0	17.0
	USA	Lost Angeles[85]	2017–19	−41.0	−57.0	−34.0		−34.0	−17.0
	USA	Louisiana[107]	2019	−10.8	61.6	−61.2	−82.3	−33.3	
	USA	New York[85]	2017–19	−29.0		−40.0		−37.0	8.0
	USA	Providence[85]	2017–19	−31.0		−26.0			20.0
	USA	Salt Lake City[85]	2017–19	−5.0		−43.0			25.0
S. America	Brazil	São Paulo[116]	2015–19				−54.3	−64.8	30.0
	Colombia[94]	Bogota[94]	2019				−64.8	15.8	
	Ecuador	Quito[91]	Pre-L	−29.0		−68.0	−48.0	−38.0	
	Peru[94]	Lima[94]	2019		−25.7	−4.6	−75.2	−27.3	−42.5

[a]Satellite data used for the study, Pre-L stands for Prelockdown period of respective study region.

Table 3 Association of new COVID-19 cases with meteorological conditions.

Location	Date	Result	Reference
Jakarta, Indonesia	Jan 1–Mar 29, 2020	Temperature positively correlated with the daily new cases. ($r = 0.392$)	119
122 cities, China	Jan 23–Feb 29, 2020	A unit rise in temperature (lag0–7) led to a 3.432% rise in daily new cases when the temperature is below 3°C.	120
166 countries (excluding China)	As of Mar 27, 2020	A unit increase in temperature and RH can reduce 5.94% and 1.23% daily new cases, respectively, at lag0–3.	121
Delhi, India	Mar 1–Jun 30, 2020	Strong Significant Correlation between Temperature and confirmed cases, 80% of the confirmed cases occurred when the temperature was higher than 30 deg. C.	122
Wuhan, China	Jan 20–Feb 29, 2020	A positive association with COVID-19 daily death counts was observed for the diurnal temperature range ($r = 0.44$), but a negative association for relative humidity ($r = -0.32$).	123
World	Mar 25–Apr 18, 2020,	The temperature has −0.45, −0.42, and − 0.50 correlation with total cases, active cases, and cases/per million, respectively.	124
China	Dec 1, 2019–Feb 11, 2020	A unit increase in temperature decreases the daily confirmed cases by 36%–57%, when RH ranges from 67% to 85.5%. A unit increase in RH decrease the daily confirmed cases by 11%–22% when temperature ranges from 5.04°C to 8.2°C	125
China	Jan 23–Mar 1, 2020	The doubling time correlated positively with the temperature and inversely with humidity ($R^2 = 0.18$)	126
New York, USA	Mar 1–Apr 12, 2020	The average temperature has a positive Kendall correlation ($r = 0.29$) with total cases	127
World (Excluding, less 5 cases)	As of Mar 8, 2020	Cool and dry places will support the virus, while extremely hot, cold, and wet will suppress it	128
India	Mar 25–Apr 30, 2020	Regions with 28–34 deg. C. and RH 35%–80% have reported 91% of the total new cases	129

Table 3 Association of new COVID-19 cases with meteorological conditions—cont'd

Location	Date	Result	Reference
52 African States	Mar 30–Apr 29, 2020	COVID-19 growth correlated positively with the wind speed ($r=0.212$), while inversely with the temperature ($r=0.624$) and RH ($r=0.551$).	130
Lagos, Nigeria	Mar 9–May 12, 2020	Inverse correlation ($r=-0.356$) between new cases and temperature, suggesting higher temperature might have decreased the spread.	131

Wind speed, RH, pressure, and city are covariates for temperature–COVID-19 association[121]; RH is covariate for temperature–COVID-19 association; confounders controlled for, including, wind speed, median age, global health security index, human development index, and population density[132]; diurnal temperature range, RH, and absolute humidity are covariates for temperature–COVID-19 association, while air pollution is confounding variable[125]; RH is a covariate for temperature–COVID-19 association[126]; RH is covariate for temperature–COVID-19 association[130]; wind speed and RH are covariates for temperature–COVID-19 association, fixed effect of countries and days are confounder.

O_3 shows a consistent increase over Europe which is in agreement with the other regions. Further, CO showed a high reduction in London (48%).[94]

A present review suggests that changes in the SO_2 are much heterogeneous, while a consistent decline in PMs and NO_2 has been observed; similarly, O_3 showed an increase across the nations. As seen in Table 2, many cities from India, China, and the USA, such as Delhi, Bangalore, Beijing, Wuhan, Lost Angeles, Louisiana, and Las Vegas, have shown significant changes in concentration.

Venter et al.[6] have investigated 10,000+ air quality stations and TROPOMI onboard the Sentinel-5P satellite to quantify changes in $PM_{2.5}$, NO_2, and O_3 using weather benchmark model trained between 2017 and 2019 to ostracize meteorological impact on air pollution. As of 15th May 2020, NO_2 and $PM_{2.5}$ showed an average of 60% [48%–72%] and 31% [17%–45%] decline, respectively, while O_3 showed slight increase by 4% [−2% to 10%] over 34 countries. Except for Denmark and Australia, every country has reported a decline in NO_2 with Serbia and Croatia observed the highest decline (see Fig. 3). Similarly, except Switzerland and Australia, all nations have shown an appreciable reduction in $PM_{2.5}$. UAE (>40%) has recorded a maximum decline in O_3, while majority of the nations have shown a negligible or increasing effect on ozone.[6]

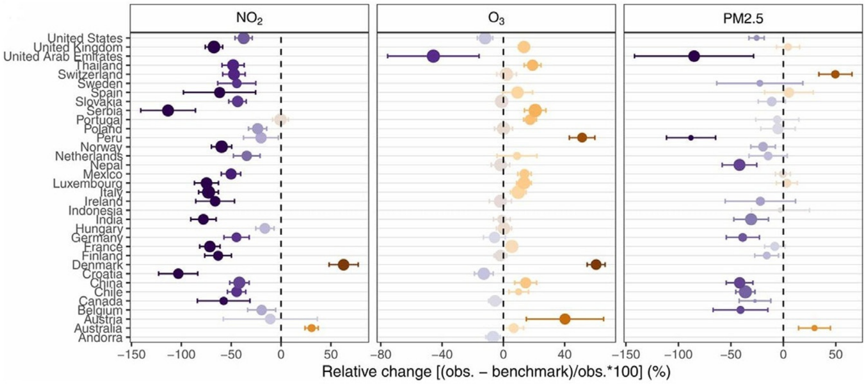

Fig. 3 Ground-level air pollution change during Jan–May 2020 with respect to the base year 2017–19.[6]

3.2 Emission sources during lockdown

Many previous emission studies have firmly agreed on the sectors primarily responsible for the unhealthy air quality, where transportation,[72,75] industries,[102] agricultural burning,[133] and residential biomass burning[73,134,135] head the list. The unprecedented reduction in air pollution during the lockdown periods owes to one of these sectors. A study conducted by Le Quere et al.[5] suggest that the power, industrial, surface transport, public, residential, and aviation activities changed by −7.4%, −19%, −36%, −21%, +2.8%, and −60%, which reduced daily CO_2 emission by 17% [11%–25%] during April 2020; however, they found that the contribution to the CO_2 reduction was mainly associated to the surface transport (43%), industry and power (43%), and aviation (10%) sectors.

In a Google mobility report (Fig. 4), it can be observed that the number of visitors in the workplaces, recreational zones, parks, public transits, and grocery stores dropped by 30% or more across many nations, while mobility increased in the residential areas by 10%, as April 2020 remained the most restricted month.[137] A policy brief over the Indian scenario by Phuleria and Navinya[77] suggests that NO_2 decline differs with the population of the city as a region with >5 million population showed ~70% decline, while <3 million showed only a 12% reduction, owing to the higher reduction in the mobility in larger cities. On the other hand, SO_2 which is primarily emitted from the power plants did not show a consistent drop during the lockdown. Activities in industries and power hubs showed some decrease, while SO_2 changes were not appreciable over the cities with no power plants

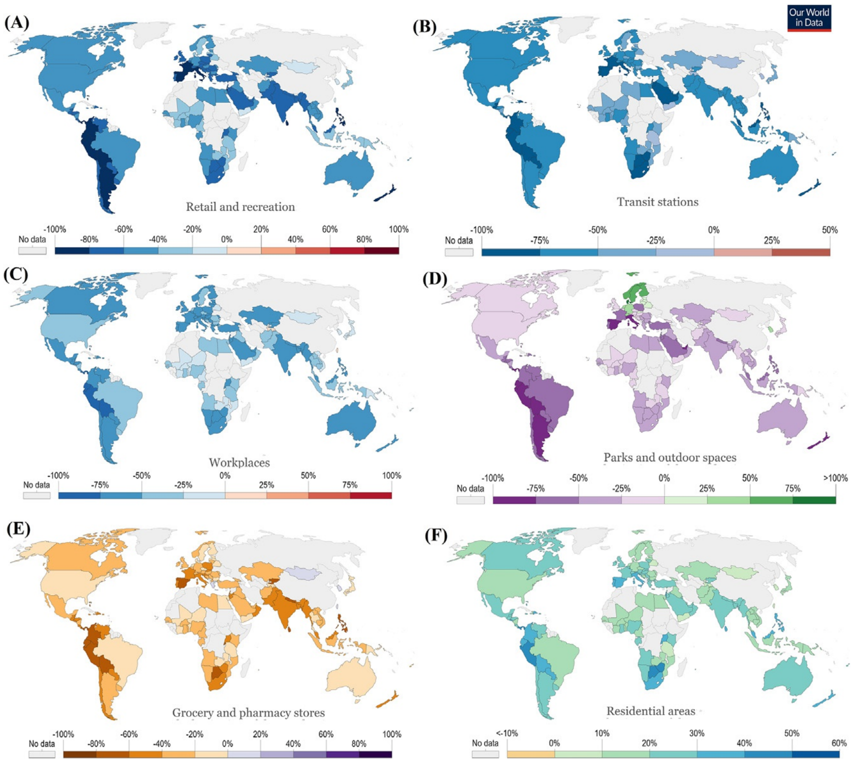

Fig. 4 Change in visitor numbers on Apr 15, 2020, relative to the baseline (Jan–Feb 6, 2020). (A) Retail and recreation, (B) Transit stations, (C) Workplaces, (D) Parks and outdoor spaces, (E) Grocery and pharmacy stores, (F) Residential areas.[136] (The index is smoothed to the moving 7-day average. Not recommended to compare levels across countries. (A) Includes restaurants, cafes, shopping centers, theme parks, museums, libraries, and movie theaters. (B) Includes public transport hubs such as subway, bus, and train stations. (D) Includes local parks, national parks, public beaches, marinas, dog parks, plazas, and public gardens. (E) Includes grocery markets, food warehouses, farmers' markets, specialty food shops, drug stores, and pharmacies. OurWorldInData.org/coronavirus CC BY.)

or industry nearby.[77] Some field burning events were observed over Central India, which suggests uninterrupted emissions from agricultural residue burning.[138] Central Electricity Authority of India (CEA) report showed the unchanged supply of electricity to the regions with respect to the requirement; however, the overall demand for the power fell down due to the shutdown of many public places during lockdown.[139] Venter et al.[6] also found the change in mobility is significantly associated with country-specific NO_2 but not with O_3 and $PM_{2.5}$. The majority of the reduction in air pollutant concentration during the lockdown has been observed between the peak traffic hours (7–10 am and 7–10 pm), which reflects the impact from the transport sector.[1] Several studies[1,5,6,10,77,140] unanimously suggest that reduced vehicular activities and power demand are the major contributors for such drastic improvement in the air quality.

3.3 Change in meteorology during lockdown and its impact on air pollution

Regional air pollution can also be influenced due to changes in meteorological parameters such as temperature, relative humidity, and wind speed.[1] However, the majority of the studies have reported the decline of major pollutants during the lockdown without considering the effect of meteorological differences.[15,80,81,84,85] Navinya et al.[1] examined the changes in temperature, relative humidity, and wind speed over 17 cities in India during the six-week long nationwide lockdown and found no significant difference between the lockdown and the previous year (2019) meteorology.[1] The magnitude of the change during the lockdown and the previous year period in temperature, wind speed, and relative humidity were $\pm 3°C$, $\pm 0.5\,m\,s^{-1}$, and $\pm 15\%$, respectively.[1] However, compared to the pre-lockdown period (Feb–Mar 2020), they observed the temperature and the wind speed to be increasing while relative humidity decreasing over India during the lockdown[1] indicating the seasonal shift from premonsoon to the summer/monsoon.

Fig. 5 shows the change in three major meteorological parameters over the globe for Apr 2020, the month when most countries had restricted their economic activities with the average for the same month during 2016–2019 given by the National Aeronautics and Space Administration's (NASA) Modern-Era Retrospective Analysis for Research and Applications, Version 2 (MERRA-2) data.[95,141–144] The changes in the meteorological parameters shown in Fig. 5 agree with Navinya et al.[1] for India. However, the changes in the meteorological conditions across the world seem heterogeneous—India, China, Eastern Europe, and Western Canada show a decrease in the temperature, while Northern Africa, Mexico, Western Australia, and central Russia show an increase. As temperature and relative humidity are inversely related, an opposite trend was observed for relative humidity, while the wind speed changed in a range of $\pm 1\,m\,s^{-1}$ over lands, where India, China, Australia, and the USA experienced a decrease; meanwhile, Canada, Middle East, and Northern Europe observed gain (See Fig. 5).

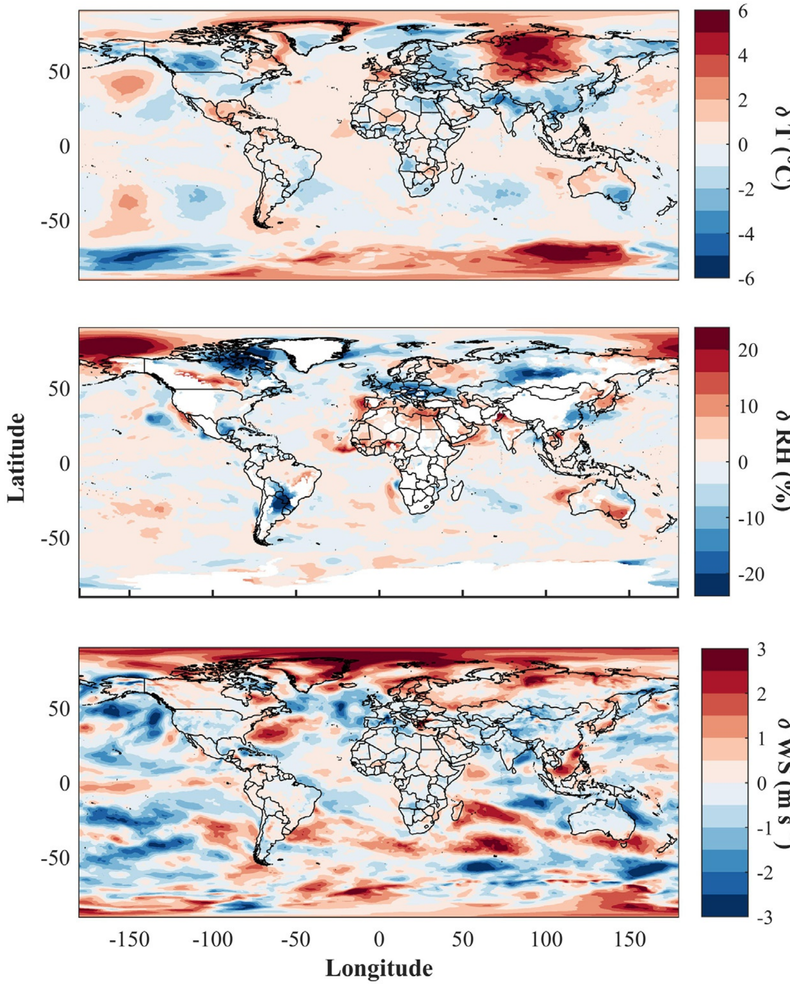

Fig. 5 Change in temperature, relative humidity (at 950hpa), and wind speed (top to bottom) during April 2020 compared to the average of the previous four years (2016–19) for April. *(Source: NASA's MERRA-2, Created by the authors using MATLAB 2017b.)*

As these meteorological changes were very small over the land, they do not seem to influence any large-scale air pollution declines across every region of the world. Hence it is very likely that these meteorological changes are not playing a vital role in air quality decline during lockdown.[145] It is accepted that the low temperature and wind speed and high relative humidity support stagnation of the air, which could lead to higher pollutant concentrations.[9] Although the regions like India observed such conditions during April 2020; however, the PMs concentration remained ~50% lower than the previous years[1,8,9,12] indicating the strong impact of the lockdown over and above the meteorological differences. Additional discussion on the effect of air pollution and meteorology on COVID-19 effects has been provided in the following section.

4. Environmental cofactors during COVID-19

4.1 Meteorology suitability for COVID-19 spread

The earlier virus outbreaks such as SARS and influenza have been studied for understanding their growth under particular weather conditions and the seasonal variability in the daily new cases. The meteorological changes during the lockdown are not just important to understand the impact of slowed economic activities and influence over air quality decline, but it has a major contribution toward the growth and spread of the virus, as a specific combination of the temperature and humidity can affect the survival of the virus. In a retrospective study that has analyzed the postevent information of the SARS outbreak, a temperature between 16°C and 28°C is suggested to support the growth of the SARS virus.[146] Another study showed that the risk of influenza could significantly increase in low temperature and humidity, while the diurnal temperature range (DTR) positively linked with the infection rate.[147] A few other studies have also reported that the temperature,[148] DTR,[149] and humidity[150] can simulate the spread rate of the respiratory viruses.

In order to understand early outbreaks, experts across the globe started investigating the spread rate of COVID-19 under various temperatures and relative/absolute humidity conditions. The correlation coefficient with lag and generalized additive models (GAM) are used to examine the relation between daily surge and meteorological conditions. Contrasting findings are reported regarding the influence of the meteorological parameters on the spread of COVID-19 (see Table 3). The disagreement among these studies can be attributed to the time period considered, lockdown measures, and average temperature for that region (see Table 3). The tropical regions such as Indonesia and India reported a positive correlation between the temperature and COVID-19 spread,[119,122,151] while global studies showed that the cool and dry condition supports spread of the virus.[121,124,128] Mecenas et al.[25] reviewed the major published articles on the subject and concluded that the hot and wet conditions would suppress the virus spread; however, the quality of the results is graded low.[25] As the outbreak is still not under control, it could get worse as the Northern Hemisphere approaches toward winter.

4.2 Air pollution, a catalyst

As 90% of the world's population lives where air quality standards exceed WHO limits, air pollution remains the biggest culprit when it comes to the deaths related to respiratory system failure, with annually ~4.2 million deaths worldwide attributed to the exposure to outdoor air pollution.[71] During the SARS outbreak in 2003, the effect of aerosols was examined and it was found that regions with the worst air quality had high mortality.[23] Similarly, many studies have examined the COVID-19 mortality with long-term exposure to $PM_{2.5}$, PM_{10}, and NO_2, as it could develop an inflammatory condition of the lungs.[21,152–157]

A preexisting inflammatory lung condition due to exposure to poor air quality, with coexisting COVID-19 infection, could be fatal; thus, many studies have quantified the share of air pollution in the COVID-19 mortality during the pandemic across the world. Statistical tools such as generalized additive model[153], simple linear regression,[158] multiple linear regression,[154,156,159] and correlation coefficients[24,152,155,160,161] are used to understand share of air pollution in COVID-19 mortality.

Wu et al.[22] have reported that US counties were having average $PM_{2.5} < 8\,\mu g\,m^{-3}$ and $> 8\,\mu g\,m^{-3}$ have an average death rate of 1.6 and 4.7 (per 100,000), respectively, thus attributing a unit increase in long-term $PM_{2.5}$ exposure to 15% increase in COVID-19 death rate. Similarly, Italian region showed a strong association of $PM_{2.5}$ and COVID-19 deaths ($R^2 = 0.53$).[160] Strengthening the argument, Ogen (2020) reported 83% of COVID-19 deaths to be associated with the regions having NO_2 more than $100\,\mu mol\,m^{-3}$. However, a city-based study over Milan[152,155] and California[24] showed a negative association between air pollution and COVID-19 mortality, which can be plausibly explained by the nonconsideration of socioeconomic indicators.[24] A $10\,\mu g\,m^{-3}$ increase in $PM_{2.5}$, PM_{10}, and NO_2 attributes to 2.24%, 1.76%, and 6.94% increase, respectively, in daily new cases over 120 cities of China, considering wind speed, RH, temperature, and city as covariates.[153] Parallel to earlier studies, Li et al.[158] have found a significant positive correlation between the daily confirmed new cases and $PM_{2.5}$ ($R^2 = 0.23$), PM_{10} (0.158), and NO_2 (0.158) over Xiaogan and Wuhan. Spatial association between confirmed infections and air pollutants such as $PM_{2.5}$ ($R^2=0.34$), PM_{10} ($R^2=0.27$), and NO_2 ($R^2=0.25$) are also reported by Fattorini and Rengoli (2020). Many studies that have used spatial data homogeneously concluded that long-term exposure to poor air quality could be lethal if coexist with COVID-19 infection.[21,22,159–161] Evidences suggested that COVID-19 mortality and morbidity are strongly associated with $PM_{2.5}$ and NO_2, while to some extent PM_{10}, illustrating the impracticality of a larger particle to reach type II alveolar cells.[157] A decreased NO_2 and $PM_{2.5}$ helped to avoid 8911 [6950 10,866] and 3214 [2340 4087] deaths from cardiovascular diseases during the lockdown in China, which outnumbered COVID-19-related deaths (4633 as of May 4, 2020), that suggest air pollution control-related policies and laws could be more helpful toward avoiding future deaths.[162]

5. Preventive policies for COVID-19 spread and air pollution

Use of alcohol-based sanitizers, social distancing up to 6 ft, avoiding crowded places, use of masks, keeping hygiene, avoid touching the face, and lockdowns are some of the preventive measures advised by the WHO to reduce the spread of COVID-19.[163] Many countries have made it mandatory to follow the aforementioned advisory and penalized for noncompliance.[164,165] Rapid task forces have been established to track potential spread to avoid community transfer in many countries. Individual tracking applications (e.g., *Aarogya Setu* by India) have been developed to keep a record of infected persons and notifying users if a potential spreader is nearby.[166] However, multidimensional aspects of the pandemic need to be considered to effectively control the spread, contain morbidity and mortality, and revive economic activities.

5.1 Post-COVID-19 preventive measures

Reduced anthropogenic emissions during the lockdown have flourished the environment, but climate change is not totally arrested. Besides, the economic growth is severely hampered, and the livelihoods of millions of people (more so the poorest of the poor) across the globe are affected. However, this temporary decline in air emissions gave an opportunity to revisit national and global policies to improve air quality, avoid climate crises, and to reduce susceptibility toward such future global crises. The pandemic has also allowed us to examine our pace to adapt to any global change. For many decades scientists have been apprising the deaths associated with air pollution, but seriousness toward this issue, in low- and middle-income countries, in particular, remained low. About 1 million deaths (as of Sep 2020) during the ~8 months of a pandemic are four times lesser than the fatalities (~4.2 million annually) due to air pollution[71] and thus warranting concerted global efforts and attention to reduce air pollution.

Masks have become a new normal during the pandemic, although these are enforced by the regional authorities to minimize and slow down the spread, but now people are understanding its significance. However, wearing a mask would also help to reduce air pollution exposure to a certain degree. Thus the practice of using a mask in high-exposure environments, especially by those who are more susceptible, e.g., asthmatics, could be promoted even after the pandemic and will require a similar level of awareness campaign. However, these are short-term measures only and governments need to rethink about the post-COVID-19 policies to accommodate future global crises such as climate change and health effects due to air pollution. Activities such as agricultural burning that influences the regional air quality for considerable months every year need to be discouraged and alternate usage of the agricultural waste need to be identified. Similarly, Ujjwala Yojana, to provide clean cooking gas by the Government of India, needs to be accelerated to reduce the residential emissions due to solid biomass cookstoves.[167]

Emissions from the transport and industrial sector are likely to go up as government removes the lockdown restriction to revive the economy after controlling the COVID-19 situation. This sudden increase in the emissions due to a drastic shift in the demand as offices and institutes open would reasonably compensate for what has been achieved during the lockdown. The transport sector may feel higher pressure due to such change in demand, resulting in overloaded vehicles, longer routes to travel. Similarly, the nonessential industries which were closed or working with minimal employees will gradually shift toward a normal working load as COVID-19 comes under control. Open street waste burning for campfires, especially in rural regions, will also start as curfew eased. Many economic and social activities will trend toward normalcy; thus, emissions will also reach to prelockdown levels.[77]

Sustainable mitigation options such as work from home, public transport, promoting electric or hydrogen vehicles, and stringency toward solid waste burning are needed to be considered in the post-COVID-19 world.[77] Encouraging green industries, scrapping the old vehicle, eliminating harmful

Table 4 Examples of policy measures to reduce air pollution while reviving the economy.[167]

Sector	Measure to stimulate green production	Measure to stimulate green demand
Transport	Vehicle scrappage policy to enable the retirement of old vehicles	Cash for clunkers scheme to incentivize modernization of the vehicle fleet
Industry	Green certification and subsidized credit lines for green production	Green procurement scheme
Agriculture	Reduce/remove urea fertilizer subsidy (excessive use of urea fertilizer is a source of secondary $PM_{2.5}$) and divert subsidy toward organic farming	
Energy	Subsidized loans for renewable energy	Cap and trade program (to generate demand for clean energy)

chemicals, and more subsidies to renewable plants can be also pivotal to reduce air pollution while reviving the economy (see Table 4).[167]

The gain in the air quality will be lost soon as the restrictions will be eased, and the industrial production and commercial activities will boost to compensate for the economic loss during the lockdown.[168] Post-COVID-19 higher emissions and their interaction with the winter-time low temperatures could be critical,[169] as more evidences are supporting air-borne transmission and the link between air quality and mortality. In addition, cold and dry regions are considered to be favorable for the long-term survival of the virus,[25] with low immunity during winter.[170] These call for better preparedness toward the threat of COVID-19 under the favorable environmental conditions for the virus survival, spread, and potency.

6. Conclusions

COVID-19, since it is observed first in Wuhan, China, has claimed ~1 million lives as of Sep 27, 2020, despite global measures including strict lockdowns for several weeks. However, this number could have been worse without such preventive steps. Major developed and developing countries such as the USA, China, Italy, India, and Mexico chose to restrict their non-essential economic activities to avoid the unconstrained spread of the virus. The majority of the countries closed mobility within and out of the country by restricting transport and vehicular activities, IT hubs, shopping malls, parks, and even government offices. Thus Apr 2020 remained globally the idlest month due to overlapping lockdowns of many countries.

Numerous studies across the world have unanimously confirmed a decline in air pollution levels, especially for the $PM_{2.5}$, PM_{10}, and NO_2, while SO_2 showed a heterogeneous response mainly attributed to the thermal power generation sources nearby, whereas surface O_3 showed a slight but consistent increase. These changes are strongly associated with the reduced anthropogenic activities, especially road transport activities as evident by the empty roads during the lockdown everywhere. Highly polluted regions of Asia such as IGP showed significant improvement in the air quality, as well as, cleaner regions of Europe and the USA also reported similar changes. The decline in the pollution levels was observed despite the usual contribution from other anthropogenic sources such as power plants, agricultural burning, and residential biomass burning and other natural sources during the lockdown, highlighting the relatively large impact of transportation sources and commercial activities on urban air quality. These changes helped climate and environment-related SDGs to gain progress; however, the duration is very short, in particular for climate-related gains and air pollutant emissions quickly reached back to prelockdown levels once the lockdown was lifted or restrictions were eased. Meteorological changes during the lockdown seem low and heterogeneous to initiate such large and consistent air pollution decline. Though the lockdown provides a very short-term draconian solution toward improving air quality, it severely affected the economic growth and livelihoods of millions of people across the world; hence, learning from this natural experiment can be exploited to frame future sustainable policies to mitigate global crises such as human health.

Other factors such as meteorological suitability for virus spread and preexisting lung conditions likely due to prolonged exposure to poor air quality have influenced the regional mortality and morbidity of COVID-19. The role of meteorology indicates mixed effects, e.g., studies using global data find cool and dry places supporting virus spread, while studies over tropical regions show a positive correlation between temperature and COVID-19 spread rate. However, the general acceptance is that hot and humid conditions will suppress the spread. Similarly, regions with higher pollution indicate higher mortality, and it is likely that the preexisting lung conditions due to prolonged exposure to air pollution make us more susceptible to COVID-19 infection and death.

COVID-19 pandemic has shown our vulnerability toward the global crisis and questioned our pace toward achieving SDGs. Air quality and GHG reduction helped SDGs to gain some benefits but for a short duration; however, the experience gained during the lockdown could help to revise policies and our progress to meet SDG commitments. Moreover, air pollution acted as a catalyst during such pandemics and likely made high exposed populations more susceptible to corona virus infection and fatality. This reflects the importance of meeting SDGs to make humans less susceptible to such global crises, and more so for the low- and middle-income countries. Governments of various countries need to keep the future global crisis in their mind while restoring the economic activities, as the cost of overcoming the crisis could be more than the cost of prevention. Hence, future policies need to be built on current experiences, and perhaps concerted efforts are needed toward renewable energy, sustainable industrial production, and smart and efficient transportation.

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