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Exploring the linkage between PM_{2.5} levels and COVID-19 spread and its implications for socio-economic circles

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A B S T R A C T

A pneumonia-like disease of unknown origin caused a catastrophe in Wuhan city, China. This disease spread to 215 countries affecting a wide range of people. World health organization (WHO) called it a pandemic and it was officially named as Severe Acute Respiratory Syndrome Corona virus 2 (SARS CoV-2), also known as Corona virus disease (COVID-19). This pandemic compelled countries to enforce a socio-economic lockdown to prevent its widespread. This paper focuses on how the particulate matter pollution was reduced during the lockdown period (23 March to April 15, 2020) as compared to before lockdown. Both ground-based and satellite observations were used to identify the improvement in air quality of Pakistan with primary focus on four major cities of Lahore, Islamabad, Karachi and Peshawar. Both datasets have shown a substantial reduction in PM_{2.5} pollution levels (ranging from 13% to 33% in case of satellite observations, while 23%–58% in ground-based observations) across Pakistan. Result shows a higher rate of COVID-19 spread in major cities of Pakistan with poor air quality conditions. Yet more research is needed in order to establish linkage between COVID-19 spread and air pollution. However, it can be partially attributed to both higher rate of population density and frequent exposure of population to enhanced levels of PM_{2.5} concentrations before lockdown period.

1. Introduction

During the initial days of December, 2019, many cases of pneumonia due to an unidentified cause started to turn up in the city of Wuhan, China. The genomic sequence of this disease showed that it is caused by a novel Corona virus, therefore, officially named as Severe Acute Respiratory Syndrome Corona virus 2 (SARS CoV-2) by International Committee on Taxonomy of Viruses (ICTV) (Lai et al., 2020). Corona virus disease, also termed as COVID-19 is the fifth pandemic to have occurred after the Spanish Flu pandemic back in the year 1918. COVID-19 spread from China to other countries by human-human transmission (Liu et al., 2020) and mainly hits the respiratory system (Waris et al., 2020). Due to its increased rate of transmission, affecting numerous people in a small span of time WHO announced SARS CoV-2 as a Public Health Emergency of International Concern (PHEIC) on 30th January 2020 (WHO Timeline, 2020). The number of new cases increased 13 times more rapidly in other parts of the world as compared to the number of new cases inside China during February, 2020. Later,

on 11th of March, 2020 COVID-19 was declared as a pandemic by WHO (Javed et al., 2020). Around 72 countries are now affected by this virus and it has caused 482,914 deaths by 25th June 2020, globally (Gardner, 2020). On February 26, 2020, Pakistan had its first confirmed corona case in Karachi. The number of cases rapidly multiplied, one reason for this could be that Pakistan shares its border with China (the epicenter for COVID-19) in the North and Iran (Ranked 10th amongst the countries with maximum number of confirmed COVID-19 cases) in the West of Pakistan. As of July 24, 2020, there were around 188,926 total confirmed cases of coronavirus in Pakistan with 72,656, 69,536, 11,483, 23,388, 9635, 892 and 1337 cases in Sindh, Punjab, Islamabad, Khyber Pakhtunkhwa (KPK), Baluchistan, Azad Jammu and Kashmir (AJK) and Gilgit Baltistan (GB), respectively (MNHS 2020).

However, there might be another aspect to this rapid increase of COVID-19 at global levels. It is known that increased air pollution can result in viral respiratory diseases affecting 10%–20% of the population. (Frontera, 2020). Exposure to criteria pollutants, for example, Nitrogen dioxide, Oxides of Sulphur, Ozone and Particulate matter (2.5 & 10) are

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known to cause respiratory and various other diseases (Saqlain et al., 2020). Thus, making population more vulnerable to contagious diseases similar to COVID-19. As there is a large effect of respiratory viral infections on the morbidity and even on mortality, it is essential to find out how the air pollutants can increase the likelihood and severity of viral respiratory infections upon exposure.

Pakistan is among the top most polluted countries of South Asia. The PM concentration in Pakistan exceeds the safe limits of WHO on regular basis as in other countries of South Asia (Sánchez-Triana et al., 2014; Khokhar et al., 2016; Anjum et al., 2020). Pakistan was ranked as the second most polluted country in South Asia in the 2018 World Air Quality Report. (Air, 2018). Lahore with an annual average PM_{2.5} concentrations of 68 µg/m³ is under “155-Unhealthy” AQI (AQICN, 2020). Studies of other major pollutants near the urban cities of Pakistan also revealed higher concentration of other criteria pollutants i.e. NO₂ and O₃ which could also contribute to further spread of respiratory disorders (Shabbir et al., 2016, Khan et al., 2018)

Increased air pollution consequently causes higher health effects. How adversely a pollutant can affect health depends upon its morphology and residence time. PM_{2.5} is very small in size and its residence time is longer as compared to PM₁₀, which makes it more convenient to penetrate in lungs, becoming part of blood circulation and reaching to other organs and causing more toxicity (Mehmood et al., 2018). PM_{2.5} can cause progressive and slow inflammation of the respiratory pathways producing more mucous and less ciliary movement which results in acute respiratory and viral infections in people exposed chronically to it. A recent study has found that increased level of PM_{2.5} also results in the transmission of influenza virus (Frontera, 2020). And this proposes a plausible linkage between COVID-19 and air pollution hotspots (especially areas with air pollutant immobility as a result of climatic conditions, local emissions and topography of that region).

Due to increasing COVID-19 cases many countries decided to impose socio-economic lockdown to prevent the spread of the disease. This step had a very positive impact on environment and air quality throughout the world and Pakistan was no exception to it. On 21st March, 2020, the Government of Pakistan issued executive orders to impose a lockdown by limiting the social interaction and economic activities from 23rd March, 2020. Various efforts were made at very local levels to ensure the lockdown in order to avoid COVID-19 spread. Besides several economic setbacks, there happened to be a gradual improvement in air quality across the world. The impacts of this lockdown were quite obvious as even residents could see with their naked eyes the blue color of the skies (less polluted) over the major cities of Pakistan (see Fig. 1). As there was less use of transport, and closure of local businesses and factories resulted in better air quality.

Therefore, the main objective of this article is to find out the difference in PM_{2.5} concentrations before and during the socio-economic lockdown in Pakistan, and to explore any relationship (if exist) between the concentrations of PM_{2.5} and COVID-19 outbreak implications in Pakistan. Further, how lockdown has helped in improving air quality and GHG mitigation.

2. Methodology and datasets

Beta-ray Attenuation Mass Spectrometer (BAMS) instrument is widely used and recommended by US-EPA in order to measure the levels of ambient particulate matter (e.g. PM₁₀, PM_{2.5}) in real time. The monitors are set to the size of PM_{2.5} using a size-specific inlet and attaching it to the analyzer. There is a radioactive source within the analyzer that produces beta rays which are passed through the glass fiber and are projected at sample deposited on a tape. Before the start of each cycle baseline attenuation levels are determined. Ambient air passes through the analyzer at the flow rate of 16.7 L/min, independent of the inlet size. The rate of beta-ray emission is constant and measured by scintillation detector. Rate at which the attenuation occurs is directly proportional to the mass of PM_{2.5} (British Columbia, 2018).

Moderate Resolution Imaging Spectroradiometer (MODIS) instrument is widely used by the aerosol community for measuring AOD. MODIS onboard Terra was launched in 2000 by NASA as part of earth observation series and collecting data with nearly global coverage with ground pixel size of 10 km × 3 km at nadir (Chu et al., 2003; Levy et al., 2013). MODIS instruments aboard Terra and Aqua crosses the equator around 10:30 and 13:30 local times respectively. Aerosol Optical Depth data was extracted using MOD04 level2 collection 6 product retrieved by using Deep Blue algorithm (Levy et al., 2013). MODIS reversion Tool Kit (MCTK) was also used for the pre-processing of MODIS data. ArcMAPv10.2 was used for geo-referencing, mapping and spatial analysis. Microsoft Excel was also used for the statistical analysis. The retrieved datasets were divided into two time durations as followed:

1. Before lockdown (1st March 2020 to 22nd March 2020)
2. During lockdown (23rd March 2020 to 15th April 2020)

The lockdown duration is based on the directives of government of Pakistan to impose a countrywide socio-economic shutdown in order to avoid spread of COVID-19 through human-human correspondence. The data for PM_{2.5} for above mentioned time periods was obtained from AirNow, which is monitored at US embassies/consulate offices in four cities of Pakistan (Islamabad, Karachi, Lahore and Peshawar). Daily averages of ambient PM_{2.5} concentrations (in µg/m³) and corresponding

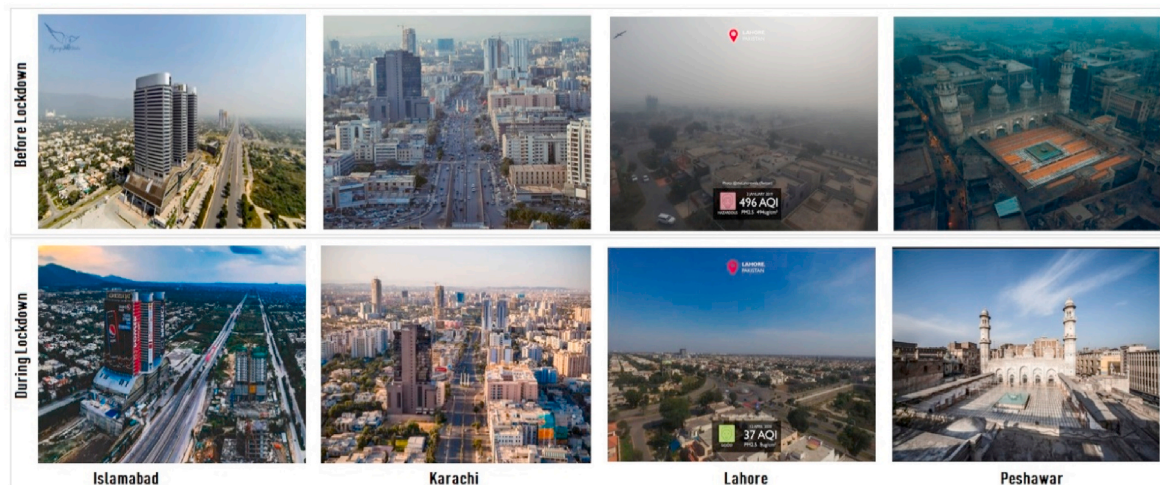


Fig. 1. Shows images taken by various individuals (residents) of these 4 cities in Pakistan before lockdown (upper panel) and during lockdown (lower panel) periods.

air quality indices were calculated for Lahore, Peshawar, Karachi and Islamabad. Percentage reduction of $PM_{2.5}$ was calculated, and respective information was presented in the form of graphs as shown in the following sections.

3. Results and discussion

3.1. Variation in aerosol optical depth (AOD)

Role of atmospheric $PM_{2.5}$ is well understood with respect to both health impacts and radiative forcing properties. However, the developing part of the world lacks proper observational networks in both space and time. Pakistan is no exception, as air quality monitoring is expensive and required consistent efforts to maintain and operate such observational network (Khokhar, 2006; 2016a; 2016b; 2017; Khokhar and Yasmin, 2018; Zeb et al., 2019). According to report by Economic Survey of Pakistan, none of the government air quality monitoring station is operational since 2010 (ESoP, 2013). Hence, we rely on satellite observations to bridge this gap to certain extent by offering long term data collection of atmospheric pollutants such as aerosol optical depth (AOD), trace and greenhouse gases over such regions (Zeb et al., 2019) in a cost effective manner (Srivastava 2020). AOD is a columnar quantity and represents the extinction (i.e., scattering + absorption) of light due to the presence of aerosols in the atmosphere, enabling AOD to be taken as a proxy for ambient levels of particulate matter. Several studies have investigated the relationship between $PM_{2.5}$ and satellite observed AOD by using fine aerosol fraction and indicated a very good correlation between both (e.g. Chu et al., 2003; Pawan et al., 2006).

Fig. 2(a) shows a map of MODIS derived AOD for a period of 22 days (1–22 March) and averaged over years 2016–2020. This shows the deteriorated air quality and high aerosol loads from ground level to the top of atmosphere over the regions hosting the anthropogenic activities. The AOD is high especially over the densely populated areas of Pakistan e.g. Punjab, Sindh, the cities that harbor most of Pakistan's business. Similarly, Fig. 2(b) represents the AOD during socio-economic lockdown period (23 March to April 15, 2020). There is a significant difference in AOD levels across Pakistan as shown in Fig. 2(c) (difference of 2(a) and 2(b)). The areas around the Indus delta with historically higher levels of AOD see significant reduction. It seems that lockdown has benefitted the air quality especially, in the major cities of Pakistan (i.e. Karachi, Lahore, Islamabad, and Peshawar). It can be clearly seen from statistics (percent reduction) in Fig. 3. The maximum reduction is observed in city of Karachi, followed by Peshawar, Lahore, Islamabad, and over all Pakistan as shown in Fig. 4.

3.2. Variations in $PM_{2.5}$ concentration

Similarly, substantial reduction in ground concentrations of $PM_{2.5}$ were observed during lock-down period (23 March –15 April 2020) at 4 different locations in cities of Islamabad, Lahore, Peshawar, and Karachi. Most significant decrease of about 58% can be seen in the city of Lahore followed by Karachi (46%), Peshawar (45%), and Islamabad (22%). The cities of Karachi, Lahore, and Peshawar have been listed among top most polluted cities of the world (WHO, 2016). This socio-economic lockdown has proven beneficial in limiting not only the $PM_{2.5}$ levels but also various air pollutants and GHG because most of the time, these are co-emitted from same activity. The observed changes in $PM_{2.5}$ concentrations and improved air quality index (AQI) of Lahore, Karachi, Islamabad and Peshawar before and during lockdown period are clearly reflected in Table 1. The difference between the two time periods can be seen as during socio-economic lockdown, every business (local/national/international) were suspended, local transport was closed, offices, educational institutes, recreational parks, restaurants, shopping malls were all closed. Grocery stores, pharmacies, and banks remained open with limited hours of operation. This whole scenario in one way created a major socio-economic set back. But on the other hand it had huge positive impact on the air quality, large scale energy conservation and relatively less spread of COVID-19.

3.3. Link of COVID-19 with densely populated and polluted areas

One thing common in these 4 cities is that they all are densely populated therefore, they are more susceptible to the spread of COVID-19. According to studies, there is a link between the spread of COVID-19 and densely populated areas. Cities with large populations are suspected to have high spread rate because of more human-human correspondence. The age of people living in an area is also a major factor along with any pre-existing health condition such as smoking, heart disease, asthma, diabetes or obesity (Florida, 2020). Another linkage is identified between larger spread of COVID-19 and higher death rate in areas that were exceedingly polluted before the pandemic. According to a study performed in USA, there is 8% increase in death rate with an increase of $1 \mu\text{g}/\text{m}^3$ of $P.M_{2.5}$ (95% confidence interval) (Xiao Wu, 2020).

Similar trend was observed with higher rate of COVID-19 spread in Karachi, followed by Lahore, Islamabad, and Peshawar (see Fig. 5). The statistics clearly indicate that huge spread in these 4 cities during lockdown and time period after lock down, primarily, it can be attributed to the fact that these are densely populated cities and human-human spread is higher. Further, the maximum percentage of casualties has been attributed to the city of Peshawar (listed among top 20 most polluted cities in the world by WHO, 2016) followed by Karachi, Lahore, and Islamabad. Partially, it could be due to in-effective

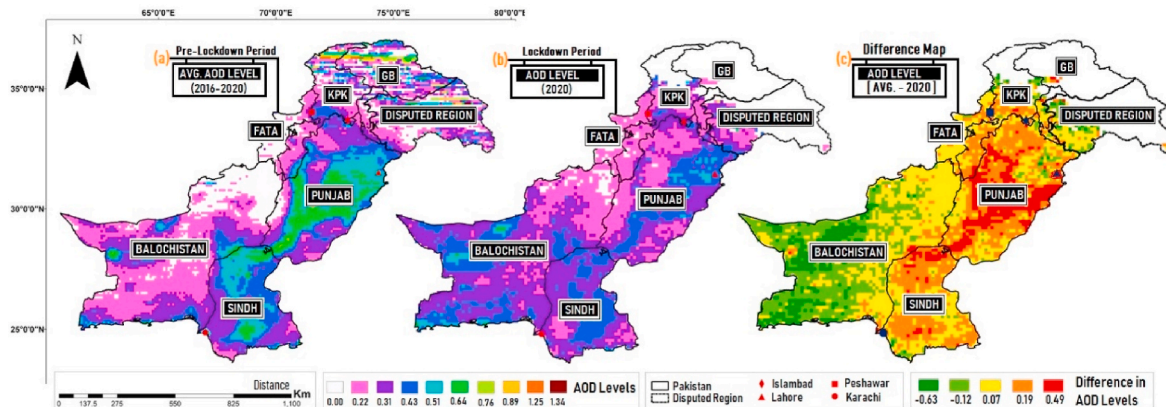


Fig. 2. (a) Average of AOD from 2016 to 2020 over Pakistan, (b) AOD level during lockdown period, (c) difference in AOD level between (a) and (b). MODIS AOD data product downloaded from (<https://ladsweb.modaps.eosdis.nasa.gov/>).

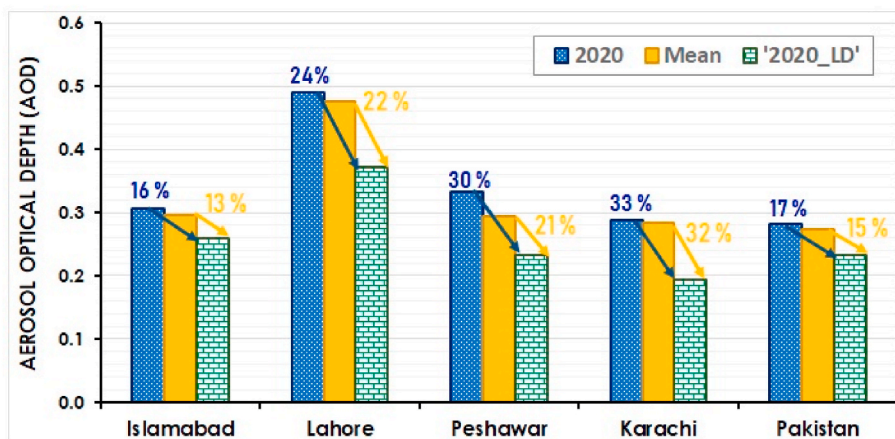


Fig. 3. Percentage reduction in AOD levels over Pakistan and major cities during the socio-economic lockdown. MODIS data downloaded from (<https://ladsweb.modaps.eosdis.nasa.gov/>).

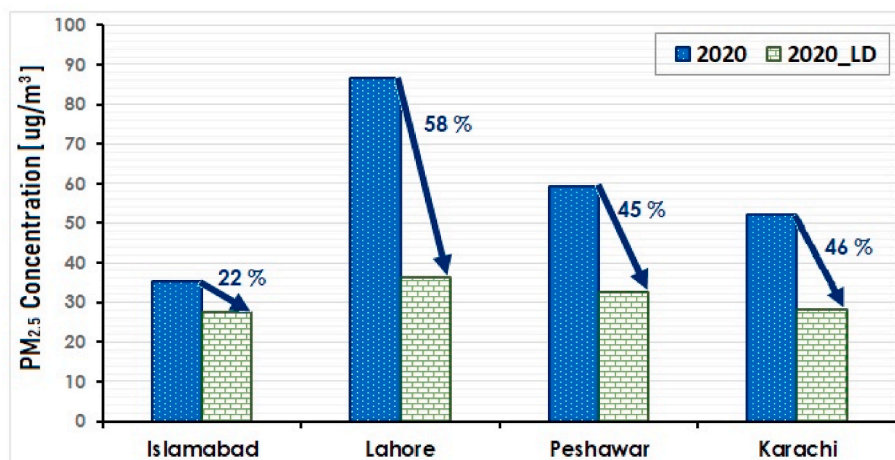


Fig. 4. Percentage reduction in ground level PM_{2.5} concentrations (ug/m³) for before and during lockdown periods. PM_{2.5} data downloaded from (<https://pk.usembassy.gov/embassy-consulates/air-quality-data/>).

lockdown, however, it can also be attributed to more susceptibility of population frequently exposed to the higher PM_{2.5} and other pollution levels as compared to population of cleaner areas. It can be further verified from the no. of deaths and percentage recovery rate in these cities as shown in table in Fig. 5. Therefore, it can be speculated that improved air quality does not only help in reducing disease burden but also reduce the vulnerability (both contamination and death rates) towards COVID-19 type pandemics.

This trend was seen all over the world as most of the countries closed incoming and outgoing international flights, people were asked to stay at homes, and there was a drastic decrease in use of motor vehicles. The consumptions patterns changed according to needs. All of this resulted in about -17% decrease in global CO₂ emissions by April 2020 as compared to the 2019 mainly just by the reduced use of transport all around the world (Le Quéré et al., 2020). It is the largest reduction in CO₂ levels to be recorded in history. Many climate scientists are pleased to experience such a substantial reduction in various atmospheric pollutants including GHGs. Whereas, on the other hand many scientists are wondering how much of efforts might have to put in for reducing the GHGs emissions in order to contain the global warming to 1.5 °C by the end of 21st century. The research shows that lockdown steps and measure taken in 69 countries which were the 97% contributors to the GHG emissions have resulted in such a sudden decrease in CO₂ concentration. It is the first notable decrease after World War II. Researchers also found

that, individually, countries are having a decrease in emissions up to 26% (Spektor, 2020). It is expected that if that lockdown remains till the mid of June, there will be about 4% decrease in emissions globally, in 2020 and if it remains till the end of this year, it can decrease up to 7%. To limit the global warming to 1.5 °C, this reduction is still short by 7.6% that is needed each year for the next decade according to the scientists (Benjamin Storrow, 2020; Storrow, 2020).

3.4. Global indirect effects of COVID-19

COVID-19 has affected almost every country and there are many impacts of this pandemic that cannot be seen directly. The most direct and evident impact of COVID-19 is on the health of humans, which is the main focus throughout the world. This pandemic has also directly affected the sectors of transport, industry, tourism, education, and offices etc. however, the direct impacts on these sectors have created indirect impacts of COVID-19 on the environment. Many impacts of COVID-19 are short-term and long-term but mainly they are considered to have a positive impact on the environment like decrease in PM_{2.5} and NO₂ concentrations, decreased noise pollution, and improvement of adaptation plans, better environmental monitoring systems, and better disaster risk management planning. There are other negative indirect impacts also occurred due to this pandemic that include decreased waste management activities, impacts on ecological systems, and current

Table 1

Enlists No. of days PM_{2.5} concentrations increased the WHO and Pak-NEQS guidelines and AQI descriptors during the both periods of before and during lockdown.

City	Time Period	Frequency of PM _{2.5} Levels Exceeding WHO Limits	Frequency of PM _{2.5} Levels Exceeding Pak-NEQS Limits	Frequency of AQI descriptors for measured PM _{2.5} levels (days)
Islamabad	Before Lock-Down (1 st -22 nd March 2020)	20 days	12 days	11 (Moderate)
				12 (Un Healthy for Sensitive Group)
	During Lock-Down (23 th March -15 th April 2020)	16 days	3 days	11 (Moderate)
				12 (Un Healthy for Sensitive Group)
Lahore	Before Lock-Down (1 st -22 nd March 2020)	21 days	19 days	4 (Moderate)
				6 (Un Healthy for Sensitive Group)
				9 (Unhealthy)
	14 (Very Unhealthy)			
During Lock-Down (23 th March -15 th April 2020)	16 days	11 days	12 (Moderate)	
Karachi	Before Lock-Down (1 st -22 nd March 2020)	20 days	16 days	7 (Moderate)
				10 (Un Healthy for Sensitive Group)
	Before Lock-Down (1 st -22 nd March 2020)	16 days	5 days	6 (Unhealthy)
				19 (Moderate)
Peshawar	Before Lock-Down (1 st -23 rd March 2020)	21 days	17 days	4 (Un Healthy for Sensitive Group)
				7 (Moderate)
				6 (Un Healthy for Sensitive Group)
	9 (Unhealthy)			
During Lock-Down (23 th March -15 th April 2020)	16 days	8 days	16 (Moderate)	
				6 (Un Healthy for Sensitive Group)

challenges faced environmental monitoring and climate services. Other indirect impacts that may have long-term impacts like the effect of present pandemic situation on achieving Sustainable Development Goals (SDGs) (Zambrano-Monserrate et al., 2020) (Cheval et al., 2020).

3.4.1. Positive indirect impacts

3.4.1.1. Improved air quality. Sudden decrease in economic and industrial activities due to lockdown caused by COVID-19 has resulted in decrease of emissions of greenhouse gases, worldwide. This results in a considerably sensible improvement in the environmental quality and climate condition. Air quality mainly depends on the human activities, due to lockdown, there was a significant decrease in the air pollution in the cities of Italy, China, and New York and considerable decrease was projected in the GHG emissions for the rest of the year.

One of the sectors that was majorly affected by this pandemic was Aviation. Aviation contributes to 3–5% of global CO₂ and 1–2% of the total greenhouse gas emissions in the environment. International Air Transport Association (IATA) has projected that about 48% decrease in aviation is expected in the year 2020. Studies have shown that even after lockdown the aviation sector will take some time before returning to normal. This indirectly results in the decrease of CO₂ and decrease in

daily temperature averages because of lessened GHG emissions (Cheval et al., 2020).

The concentration of NO₂ has also decreased in this pandemic lockdown for example, Milan had 21% less average NO₂ levels for the week of 16–22 March, 2020 as compared to the same week of 2019. Bergamo, Barcelona, Madrid and Lisbon experienced a decrease of 47%, 55%, 41% and 51%, respectively in average NO₂ concentrations for the same week in 2020 as compared to that week of 2019 (Cheval et al., 2020). NO₂ levels in Wuhan and China decreased to about 22.8 µg/m³ and 12.9 µg/m³, respectively (Zambrano-Monserrate et al., 2020).

3.4.1.2. Decrease in noise pollution. Transport sector is one of the main causes for both greenhouse gas emissions as well as noise pollution. As the governments of many countries issued the lockdown and quarantine orders to protect the people from this pandemic, there was seen a considerable decrease in traffic flow on the roads, for example, the truck and car traffic in Vienna was decreased to 50% and 52%. This not only resulted in the decrease of emissions of GHGs but also a significant amount of decrease in noise level was also observed that was produced from horn honking and other vehicles. Also, this reduction in noise levels resulted in improved detection of seismic waves and earthquake prone areas and the seismographic records were enhanced positively

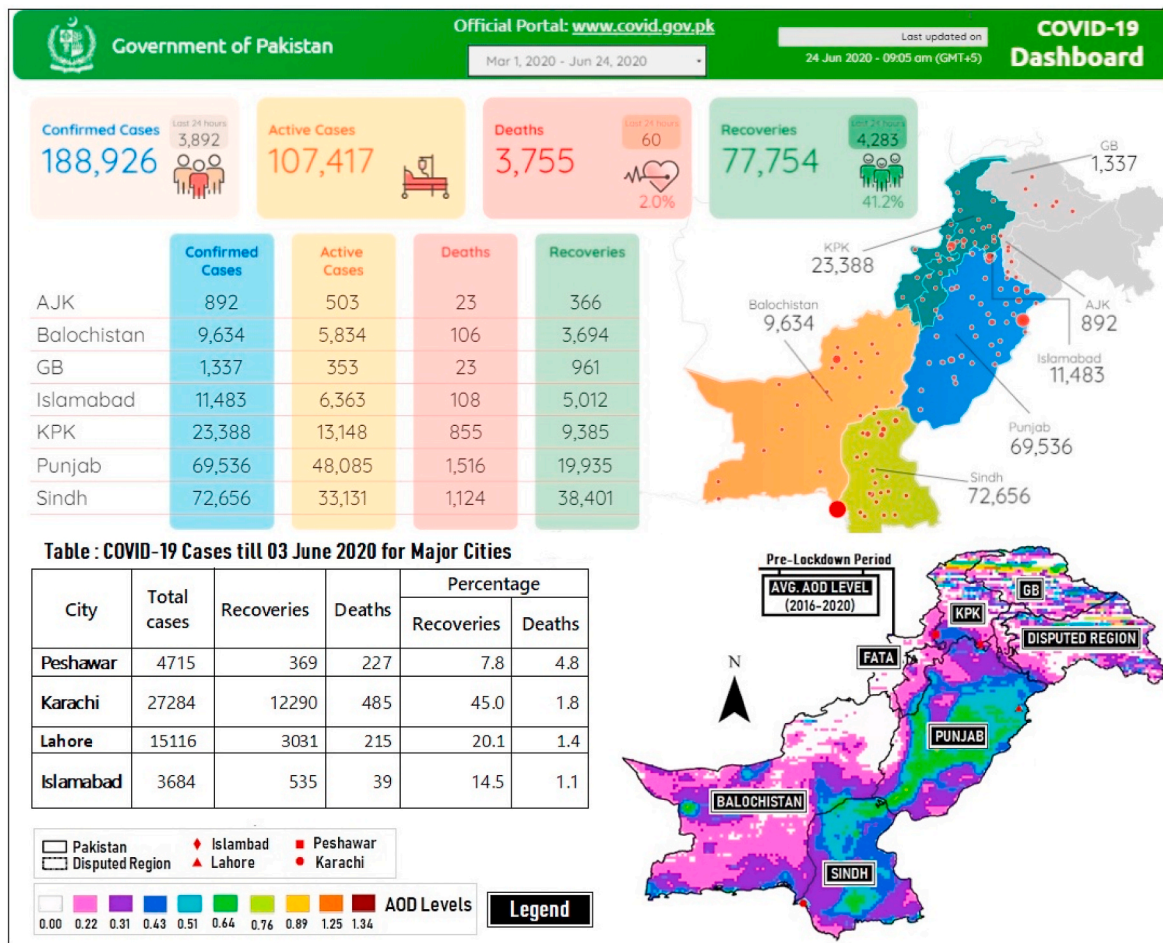


Fig. 5. The dashboard of Ministry of National Health Services developed for COVID-19 information. It is further amended by adding information about COVID-19 cases registered, recovered and deaths reported in 4 major cities till 3rd June 2020. Average AOD map is also presented. Data obtained from(<http://covid.gov.pk/>).

(Cheval et al., 2020).

3.4.1.3. Effect on water bodies. Due to COVID-19 lockdown, in areas where there was boating travel a common means of transport e.g. Italy and various tourists locations have faced an immediate positive impact on water bodies by decrease in the water pollution as no such boating travel was being used (Cheval et al., 2020). A study performed on the Suspended Particulate Matter (SPM) in a freshwater lake, Vembanad Lake of India to find out if there was a change in SPM concentration during these lockdown conditions. The results showed that there was a 34% decrease in SPM as compared to the concentrations of previous years (Yunus et al., 2020).

3.4.2. Negative indirect impacts

3.4.2.1. Decreased waste management activities. Majority population all around the world is in isolation and is staying at home due to which the domestic waste generation has peaked. Along with the domestic waste, the hospital waste has also increased. Discarding of Personal Protection Equipment (PPEs) on the roadsides and near the shoreline is increasing as the time of lockdown in this pandemic is increasing (Cheval et al., 2020). A news article published in DAWN tells about the increased waste accumulation in Karachi, Pakistan. Sindh Environment Protection Agency (SEPA) has been inactive for almost two months that has led to the excessive hospital waste and domestic waste unattended on the streets of the city. The article says that there has been no proper disposal mechanism for COVID-19 waste has been developed till now and none of

the hospitals are given any sort of instructions to combat this problem. SEPA has the responsibility for the disposal of the hospital or otherwise hazardous waste so that none of the public is affected by it, but the organization has been inactive and no such measures has been taken as of yet (Ilyas, 2020).

3.4.2.2. Effect on ecological system. Speaking from an ecological point of view, there can be seen a link between our society and the ecosystem. COVID-19 is the result of climatic alterations in the ecosystem because of habitat destruction of many species, introduction of invasive species, and changes in the distribution pattern of species. Around 300 animal welfare organizations wrote letter to World Health Organization (WHO) to consider the relationship between the occurrence of pandemics and animal markets. Deforestation is also another cause that increases the interaction of human to wild animals that may also result in transmission of some alien virus or specie that can cause such a catastrophic effect as caused by this COVID-19 pandemic and the ones before it.

The pandemic has affected the ecological research and field work that has resulted in the limitation of research activities causing consequences for the specie and habitat conservation. This has resulted in the assessment of the long-term practicality of various wildlife conservation programs e.g. Global Environment Fund (Cheval et al., 2020).

3.4.2.3. Challenges in environmental monitoring and climate services. The COVID-19 has highlighted that there must be better preparedness for the monitoring of environmental and climatic services. The pandemic has brought up the need for access to real time and long-term data that can

help the policy makers to identify the different reactions taking place in different areas in this time of crisis. The sustainability issues this pandemic has identified has caused the environmental scientists to strengthen the monitoring capability. The pandemic has significantly prejudiced the production and availability of weather forecast data because of decreased quality and quantity of weather observations by aircrafts. Climate services along with the ocean and remote area observations have also been biased by this pandemic.

Better monitoring can help many countries to study and identify the spread of this novel COVID-19. The tools established now, lessons and data from the present, can be used in the future to efficiently combat the spread of such a disease (Cheval et al., 2020).

3.4.3. Long-term effect of COVID-19 on SDGs

It is expected that the current situation of COVID-19 can affect the future environmental and economic policies on an international scale. "Transforming our World: the 2030 Agenda for Sustainable Development" include 17 SDGs which focus mainly on attaining sustainability by 2030 and removal of poverty. These SDGs have faced a direct effect due to COVID-19 and are expected to experience long-term effects as well. Many of these SDGs are directly related to the health of population and urban areas. The execution and idea of this agenda should be reviewed on the basis of the findings of present conditions that include exposure, vulnerabilities and resilience seen during this global disaster (Cheval et al., 2020).

3.5. Relationship between environmental factors and the spread of COVID-19

There have been a few cases in history where the spread of viruses such as the West Nile virus in Europe has been linked with meteorological conditions, i.e. weather, temperature variations, etc. That is why researchers are interested in studying the link between the spread of COVID-19 and meteorological conditions i.e. temperature variations and other weather conditions changes such as humidity. After the initial spread of the COVID-19 virus in mid-December, the virus quickly spread from China to regions with cooler weather conditions such as Europe and North America. After the research on the initial spread, the findings indicated that like pneumonia, COVID-19 also causes respiratory disorder closely associated with variations in weather and climatic conditions between different regions (Mazhar et al., 2020).

A study performed in China examining the relationship between temperature variations and COVID-19 found that temperature is an environmental driver for the outbreak of this pandemic in China. According to Shi et al. (2020), increased temperature resulted in a decreased rate of transmission, outbreak magnitude, and rate of infections.

Other meteorological parameters are also important for studying the spread of similar respiratory diseases like influenza and Severe Acute Respiratory Syndrome (SARS). A study in China explored the relationship between the death rate caused by COVID-19 and the varying environmental conditions i.e. varying temperature and humidity. A positive relationship was observed between the death rate and diurnal temperature range while anti-correlated with relative humidity (Ma et al., 2020). Therefore, determining the potential influences of meteorological/environmental parameters is mandatory in order to restrain the spread of COVID-19 and other precautionary measures.

Unlike the case of China, no definitive link could be established between the spread of COVID-19 and temperature in Pakistan. According to available datasets obtained at the provincial level from the Government of Pakistan's COVID-19 portal and weather archives, no significant relationship was found between the spread of COVID-19 and temperature variations. First, the spread of COVID-19 in Pakistan was relatively less and dealt effectively with socio-economic lockdown. Second, it was mainly due to increased human-human interactions. However, it was observed that the spread of COVID-19 was higher in areas with high

pollutant concentrations, such as the major cities of Pakistan mentioned in this study and other parts of the world.

As COVID-19 is a respiratory disease and there is an established link between the spread of (past) respiratory diseases in areas exposed to high air pollution levels (Frontera, 2020). It can be speculated that the spread of COVID-19 in the areas where the pollutant concentrations were higher than other areas caused more health impacts derived from this pandemic.

A sharp decline in pollutant emissions (GHG and other toxic gases) has been observed during socio-economic lockdown after the COVID-19 outbreak, and such a decline in global emissions have not been observed in the past 25 years. This decrease in global emissions might have consequences for the entire planet, causing a possible cooling effect. However, this depends upon the already accumulating concentrations of carbon dioxide and other atmospheric greenhouse gases. There are also possibilities that the reduced emissions will peak again after the global lockdown is lifted, and greater than before when factories and businesses attempt to balance their losses through increased activities.

As a result of this remarkable decrease in emissions, climate change and the COVID-19 pandemic have opened new avenues in climate-related research. While the growing impacts of climate change have long demanded a reduction in global emissions, this pandemic has lowered global emissions more successfully than ever in the past.

Many countries, including Pakistan, have taken precautionary measures and introduced emergency reforms to combat this pandemic. However, it is uncertain whether this pandemic will help reduce long term carbon emissions and hence cause a cooling effect, or the world will bounce back to its previous emission concentrations (Sheikh, 2020). There are many things that countries can glean from their battle against the COVID-19 virus and incorporate them into the fight against climate change. Further, it has urged the global communities to ponder about having frequent socio-economic lockdown in areas with more carbon emissions in order to meet the set targets of the Paris agreement. However, there is an urgent need and demand from the scientific community to work on it in order to suggest the intensity (weeks/months) and frequency (every 6/12 months) of such lockdowns without compromising on socio-economic development.

3.6. Effect of COVID-19 on the economy of Pakistan

This pandemic has significantly impacted the world economy and its disproportionate impacts have been felt throughout the globe, with some countries being more affected than others. Economically, Pakistan was already under pressure before the imposed lockdown further exacerbating the situation. The most severe damages were undergone by the daily wagers, micro, and medium-sized businesses. Whereas several industries considered the cornerstone of the country's economy, such as the textile industry, were also severely affected as many orders for textile imports were canceled during the COVID-19 period. The rate of unemployment increased while the economic growth decreased rapidly. The GDP growth of Pakistan in 2018 was 5.8%, and it fell to 0.98% and is expected to decrease further due to the financial constraint imposed by the COVID-19 lockdown (Saleem, 2020).

As mentioned previously, small and medium-sized businesses were most seriously affected because of disruptions in their daily activities and the limited class of customers available. The onset of COVID-19 and the subsequent fall of these small enterprises have greatly affected the economy at large due to socio-economic lockdown. Many of these businesses are not sustained because of major losses during this pandemic. These small businesses are vital for the economy of a country as they increase the employment ratio and provide income to the country that is not earned from the outside. In Pakistan, these small and medium-sized businesses contribute to about 40% of the GDP. These are present in rural as well as urban areas of Pakistan. Medium and small-sized businesses are major presenters in the agricultural, retail, wholesale, and trade sectors of Pakistan. These businesses face financial

problems, shortage in supply chain and orders, and reduction in customer ratio (Shafi et al., 2020).

3.7. Overcoming the negative impacts of COVID-19

This pandemic has adversely affected the world in every possible aspect, be it economic, social, or health related. Many countries are taking steps to minimize adverse impacts. Similarly, the government of Pakistan has also taken steps to secure the country from socio-economic setbacks. Pakistan Humanitarian Response Plan for COVID-19 Pandemic has been established to determine the possible negative impacts that this outbreak can cause and possible mechanisms to control and overcome them. Some of the salient features are listed below:

- In response to the **impacts on public health**, the government has issued a surveillance and screening procedure for people at all types of entry points.
- A health declaration form (HDF) is required to be filled by the passengers before traveling.
- Following the proper biosafety standards, the labs in major cities are designated to collect samples from suspected COVID-19 patients.
- Many mobile labs are being established at various locations in different cities for sample collections.

In response to the **impacts on the economic system**, the government of Pakistan has established a multi-sectoral relief fund for COVID-19 challenges.

- Government of Pakistan (GoP) has allocated PKR 1.25 trillion for combating the problems and challenges faced due to COVID-19.
- 1.2 billion dollars for providing relief to the daily-wagers and laborers
- 600 million dollars for the industrialists and exporters
- 600 million dollars for providing relief to agriculture and SMEs.
- 300 million dollars for the Utility Stores Corporation (USC) to provide basic eating supplies, including flour, pulses, sugar and cooking oil, on subsidized rates.
- 1.69 billion dollars to obtain 8.2 million tons of wheat this season.
- The prices are reduced by 15 rupees each for per liter petrol, diesel, kerosene, and diesel oil.
- 90 million dollars to be experienced on tax break to provide relief on health and food supplies
- 600 million dollars for providing relief for residual/energy fund.

In addition to above-mentioned steps taken, there is ongoing national coordination, planning, and monitoring program for the prevention of further damages (OCHA, 2020).

3.8. Practical implications of this study

3.8.1. Challenges faced

The main challenge faced in this study was the availability of data at finer spatial scales, such as the city level. Due to the unavailability of data, the complete relationship between the spread of COVID-19 with various environmental parameters could not be studied.

3.8.2. Future work

As the number of COVID-19 cases in Pakistan have declined drastically up till September, 2020. Therefore, it is mandatory to analyze COVID-19 daily cases in major cities of Pakistan on finer spatial and temporal scales, and find out if there was any existing link to meteorological conditions and/or the smart socio-economic lockdown was the key factor as it wasn't the case in neighboring countries. Furthermore, there is need to explore the COVID-19 spread and consequent morbidities such as respiratory and cardiovascular diseases and their relationship to an increased level of air pollution as a driving factor.

3.8.3. Recommendations

It is recommended that:

- Proper policies should be made to ensure the health safety of the public.
- There must be proper control measures implemented to prevent the wide and rapid spread of COVID-19, keeping in view the role of meteorological and other factors
- As air pollution can be linked with the widespread of COVID-19 and consequent morbidity, the government must take measures to ensure air pollution levels within safe limits.
- Further studies must be performed to determine if the cases or deaths of COVID-19 are associated with changing environmental conditions.

3.9. Recommended policies and real-life applications

There should be policies in place to protect people and the environment at the same time. As COVID-19 has affected almost every sector, the policies should be as practical and easy to implement with the least implications to socio-economic development. Some of the following policies which can be useful in reducing the impacts of COVID-19 are as under:

As the lockdown has proven to be beneficial for our environment and restricting the COVID-19 spread, the government should take steps to keep the anthropogenic emissions in check for the future. Some of the following steps can be employed for that purpose:

- The government should implement smart lockdown even after COVID-19 to regulate the rate of anthropogenic emissions within permissible limits.
- The factories and industries should fix operation timings, and in particular, setting off during the peak emissions hours.
- No further provision/banning of some polluting industries located near residential areas as they produce smoke and other pollutants that can be harmful to people who are suffering from any respiratory disease.

In order to mitigate the impact of COVID-19 on businesses, the following steps can opt:

- To assess the operational and financial impacts of COVID-19 on their enterprise either on a small or large scale.
- Policies for managing the flow of cash through the supply chain must be regulated and subsidized to help to keep the supply chain functions.
- Many business contracts and commitments have become unsustainable for small businesses in order to minimize the adverse impacts of these contacts, policy interventions for the provision of subsidies and relief in taxes need to be implemented as soon as possible. (Sabina Softić, 2020).

4. Conclusions

Both satellite and ground-based observations indicated that air quality, especially PM_{2.5} levels has been largely improved all around Pakistan. Significant improvement has been observed in the measured concentration of PM_{2.5} levels at Lahore (58%), Karachi (45%), Peshawar (46%), and Islamabad (22%) as a result of the socio-economic lockdown imposed by the government of Pakistan. These cities host the most number of COVID-19 cases which can be attributed to their dense populations, however, poor recovery rate and relatively better tertiary level hospital facilities as compared to the rest of Pakistan indicates that as the population is most frequently exposed to very high level of PM_{2.5} levels and other air pollutants (above Pak-NEQ and WHO guidelines) therefore, impact of COVID19 were more severe and casualty rates were

higher when compared to the rest of the country. Therefore, it can be speculated that the population residing in major cities (frequently exposed to a higher level of PM_{2.5} levels) is more susceptible than the population living in areas with less exposure to PM_{2.5} levels. Therefore, limiting socio-economic activities may result in an economic deadlock but it can improve the air quality and ease the economic burden of states indirectly by lowering the cost of disease born by subsidized health institutes in Pakistan. However, lots of efforts and research needed to address a logical question; how frequently is needed a socio-economic lockdown to breathe clean air and to mitigate climate change?

Declaration of competing interest

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

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