Impact of COVID-19 Lockdown Measures on Air Quality in Khyber Pakhtunkhwa Province: A Google Earth Engine Based Study

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Air pollution poses a critical challenge to urban sustainability and public health. The COVID-19 lockdown created a unique opportunity to study the effects of reduced human and industrial activities on air quality. In rapidly urbanizing regions, such as Khyber Pakhtunkhwa, the concentration of pollutants like Carbon Monoxide (CO), Nitrogen Dioxide (NO2), and Sulfur Dioxide (SO2) has escalated, threatening public health. This study utilizes Google Earth Engine (GEE) and Sentinel-5P TROPOMI satellite data to assess changes in NO2, CO, and SO2 levels during Pakistan's nationwide COVID-19 lockdown. Results show a significant reduction in pollutant levels, offering insights for developing long-term air quality improvement strategies and policies to mitigate respiratory health risks.
Keywords: Google Earth Engine (GEE), Tropomi, Air Quality, Air Pollution, Covid-19, Lockdown.

Introduction:

The gases in the Earth's atmosphere, including oxygen, nitrogen, and ozone, are essential for sustaining life and preserving ecological balance [1][2]. However, rising atmospheric pollution has placed immense pressure on these resources, posing a significant risk to ecosystems worldwide [3]. Air pollution, often referred to as the contamination of the air by chemical, biological, or physicalagents, has become a critical global issue, especially in rapidly urbanizing and industrializing regions [4]. Poor air quality, characterized by harmful pollutants like carbon monoxide (CO), nitrogen dioxide (NO2), sulfur dioxide (SO2), and particulate matter (PM2.5 and PM10), can severely affect public health and environmental sustainability [5].

In March 2020, the World Health Organization (WHO) declared COVID-19 a global health crisis, significantly disrupting human activities worldwide. This resulted in a temporary decline in industrial operations, vehicular traffic, and other pollution-producing activities (WHO, 2020). This sudden cessation of human-induced activities created a unique "natural laboratory" for examining the impact of reduced emissions on air quality. Numerous studies have reported improved air quality during the COVID-19 lockdown, especially in regions like South Asia, where air pollution levels have historically been elevated [6][7]. An analysis in 2020 found that nitrogen dioxide (NO2) levels in parts of Southeast Asia, including Indonesia, dropped by 40%, which was linked to reduced transportation and industrialactivities [8]. In Metro Manila, NO2 concentrations decreased up to45% due to a significant reduction in vehicular emissions and power consumption during the lockdown [9]. These reductions underscore the impact of human activity on regional air quality and offer insights into potential environmental policies.

The Tropospheric Monitoring Instrument (TROPOMI), onboard the Sentinel-5P satellite, represents one of the most advanced tools for atmospheric pollution analysis. It facilitates high-resolution monitoring of pollutants such as nitrogen dioxide (NO2), carbon monoxide (CO), and sulfur dioxide (SO2), providing critical insights into the spatial and temporal variations in air quality [5]. The integration of Google Earth Engine (GEE), a cloud-based platform for processing large-scale geospatial data, further enhances the ability to visualize and analyze satellite-based atmospheric data [10]. This combination of remote sensing and advanced analytics presents a powerful approach for assessing the impacts of air quality changes during events like the COVID-19 lockdown [11].

The COVID-19 pandemic brought about unprecedented changes to human activities, manyof which had a beneficial effect on the environment, particularly air quality [12]. Studies have shown a substantial reduction in key air pollutant levels during the lockdown period across multiple regions [13][14]. The reduction in industrial output and vehicular emissions, combined with a general decrease in economic activity led to noticeable improvements in air quality, as reported in several countries [15][6].

The author [16] analyzed the impact of the initial COVID-19 lockdown on nitrogen dioxide (NO_2) levels in Thessaloniki, Greece, reporting a modest 4.03% reduction during the lockdown period. Their findings indicate that air quality improvements are highly dependent on the intensity of local emission sources and the stringency of lockdown measures. Similarly, [17] examined NO_2 and ozone (O_3) concentrations in Tehran and Arak, Iran, using Sentinel-5P data via Google Earth Engine (GEE). They found a 3.5% decline in NO_2 in Tehran and a more substantial 20.97% decrease in Arak during the lockdown, accompanied by a reduction in ozone levels, which underscores the effectiveness of lockdown restrictions in mitigating pollution, especially in industrial areas.

The author [18] studied the indirect environmental effects of lockdowns in Jharkhand, India, utilizing MODIS-NDVI data processed through GEE. They observed a 19% increase in vegetation greenness, highlighting how reduced human activities can enhance vegetation health. [19] integrated Sentinel-5P data with machine learning techniques to quantify pollution levels, demonstrating the utility of geospatial technologies like GEE in environmental monitoring.

Similarly, [20] reported a significant decline in NO_2 levels across China during the lockdown, illustrating the potential of remote sensing to assess the impacts of reduced human activity on air quality.

In Bangladesh, [21] documented substantial decreases in carbon monoxide (CO), sulfur dioxide (SO_2), and aerosol optical depth (AOD) during the lockdown, although ozone levels showed mixed trends. This suggests that the interactions between air pollutants and environmental factors are complex and may vary by region and pollutant type. [5] analyzed nitrogen dioxide (NO_2) and sulfur dioxide (SO_2) concentrations in Turkey from January 2019 to September 2020 using Sentinel-5P and MODIS data on GEE. Their findings emphasize the role of high-resolution satellite data in understanding air pollution dynamics and providing insights for policy interventions.

The author [12] conducted a comprehensive analysis of air pollutant responses to the lockdown in China, utilizing both satellite and in-situ data. They found a significant reduction in NO_2 levels, while PM2.5 concentrations exhibited varied trends depending on regional characteristics. This underscores the diverse impacts of lockdown measures on different pollutants and regions. In the context of Pakistan, studies on air quality changes during the COVID-19 lockdown are limited. [22] utilized Sentinel-5P data on the GEE platform to assess changes in O_3, NO_2, and CO concentrations across the country during the lockdown, identifying notable reductions. Similarly, [23] found significant decreases in SO_2 and CO levels, with a smaller reduction in PM2.5 and an increase in O_3, attributed to reduced NOx levels and higher temperatures during the lockdown. [24] reported a 21.10% reduction in NO_2 emissions across South Asia, including Pakistan, highlighting the potential for short-term air quality improvements with reduced industrial and vehicular activities.

The author [25] focused on the impacts of rapid urbanization and industrialization on NO_2, land surface temperature (LST), and vegetation health in Lahore and Faisalabad, Pakistan, from 2019 to 2022. Their study revealed substantial increases in NO_2 and LST and a decline in vegetation health, stressing the need for stringent environmental regulations in these rapidly growing urban centers. Collectively, these studies illustrate the varying effects of COVID-19 lockdowns on air quality and underscore the critical role of remote sensing technologies like Sentinel-5P and GEE in monitoring these changes. While many regions experienced improvements in air quality due to reduced industrial and vehicular activities, others exhibited more complex interactions between pollutants and environmental factors, suggesting that mitigation strategies should be tailored to local contexts.

This comprehensive review of the literature indicates that while a few studies have investigated air pollution levels in Pakistan using GEE during the lockdown, no in-depth study has specifically focused on the Khyber Pakhtunkhwa (KP) province. Therefore, this study seeks to fill that gap by providing a detailed analysis of air quality changes in KP during the COVID-19 lockdown using GEE and Sentinel-5P data. It will serve as a foundational guide for future research in this region, contributing valuable insights into air pollution mitigation strategies and the broader implicationsfor public health. The aim of this study is to assess the impact of lockdown measures during COVID-19 on air quality in Khyber Pakhtunkhwa (KP) province, Pakistan, by analyzing spatio-temporal variationsin key air pollutants, including nitrogen dioxide (NO2), sulfur dioxide (SO2), and carbon monoxide (CO). The following are the objectives of the study;

- To find out the impacts of lockdown on air quality in KP.
- To assess the variations in the atmospheric concentrations of toxic gases, including NO_2, SO_2, and CO, before, during, and after a lockdown period.

Material and Methods:

This study aims to examine the spatio-temporal variations in air pollutants, including nitrogen dioxide (NO2), sulfur dioxide (SO2), and carbon monoxide (CO), in the Khyber Pakhtunkhwa (KP) province of Pakistan. The COVID-19 lockdown in Khyber Pakhtunkhwa (KP) began on March 23, 2020, when the provincial government, following other regions of Pakistan, imposed restrictions to curb the spread of the virus [26]. This was part of a nationwide effort to respond to the rising cases of COVID-19 across the country. The province implemented various measures, including closing schools, suspending public transportation, and restricting social gatherings. The lockdown in KP was eased gradually from mid-May 2020, as the government introduced "smart lockdowns" in certain areas [27]. However, stricter measures were reintroduced when necessary, depending on localized COVID-19 surges. By August 2020, most of the restrictions were lifted, allowing businesses and daily life to resume with some safety protocols in place [28]. The analysis covers periods before, during, and after theimplementation of COVID-19 lockdown measures using Sentinel-5P satellite data and the GoogleEarth Engine (GEE) platform.

Study Area:

Figure 1 illustrates the geographical location of Khyber Pakhtunkhwa (KP), a province situated in the northwestern region of Pakistan, which is the primary focus of this research. The province is situated between approximately 34.9526° N latitude and 72.3311° E longitude, covering an area of about 101,741 square kilometers (39,282 square miles). Khyber Pakhtunkhwa (KP) shares its western and northern borders with Afghanistan, while it is bounded to the east and northeast by Azad Kashmir and Gilgit-Baltistan. The province is bordered by Punjab to the southeast and by Balochistan to the southwest. KP consists of 39 districts, divided into seven administrative divisions, and had anestimated population of over 35 million people as of 2017. The province is characterized by diversetopography, including mountains, submontane regions, and plains. It is divided into two geographical zones: the northern zone, which spans from the Hindu Kush mountains to the Peshawar basin, and the southern zone, extending from Peshawar to the Derajat basin. KP faces significant air pollution challenges, especially in densely populated cities like Peshawar, Mardan, Abbottabad, and Swat. Major sources of pollution include industrial emissions, vehicular traffic, brick kilns, and biomass burning for cooking and heating. Natural factors, including dust storms and seasonal variations, also play a significant role in contributing to air quality challenges.

Data Collection:

The study employed a combination of satellite data and advanced geospatial analysis tools to assess air quality changes in Khyber Pakhtunkhwa (KP) during the COVID-19 lockdown. Sentinel-5P satellite imagery, obtained from the Tropospheric Monitoring Instrument (TROPOMI), was utilized to monitor the spatial and temporal distribution of nitrogen dioxide (NO_2), sulfur dioxide (SO_2), and carbon monoxide (CO) across the region. This analysis covered the period from March 2020, marking the onset of the lockdown, to August 2020, post-lockdown. To establish a baseline, the same timeframe from 2019 was analyzed for comparative purposes, enabling a comprehensive assessment of air quality variations before, during, and after the lockdown period.

Data Acquisition and Justification:

The choice of Sentinel-5P data and Google Earth Engine (GEE) was based on their unique capabilities to provide comprehensive and high-resolution atmospheric measurements, essential for understanding air quality dynamics over large areas. Sentinel-5P, equipped with the Tropospheric Monitoring Instrument (TROPOMI), offers daily global coverage with high spatial resolution (up to 7 km x 3.5 km), which is particularly advantageous for monitoring air pollutants like NO_2, SO_2, and CO at a fine scale. This enables the detection of pollution patterns and trends that might be missed by ground-based monitoring systems. Additionally, TROPOMI's ability to measure multiple pollutants simultaneously allows for a more holistic view of the air quality.

Google Earth Engine (GEE) was selected as the data processing platform due to its cloud-based architecture, which facilitates the handling and analysis of large datasets with complex algorithms. GEE provides a powerful platform for accessing, processing, and visualizing satellite data in real time, making it ideal for studies requiring large-scale temporal and spatial analyses. Its extensive data catalog and advanced geospatial processing capabilities, combined with an intuitive coding environment, allow for efficient and reproducible analyses.

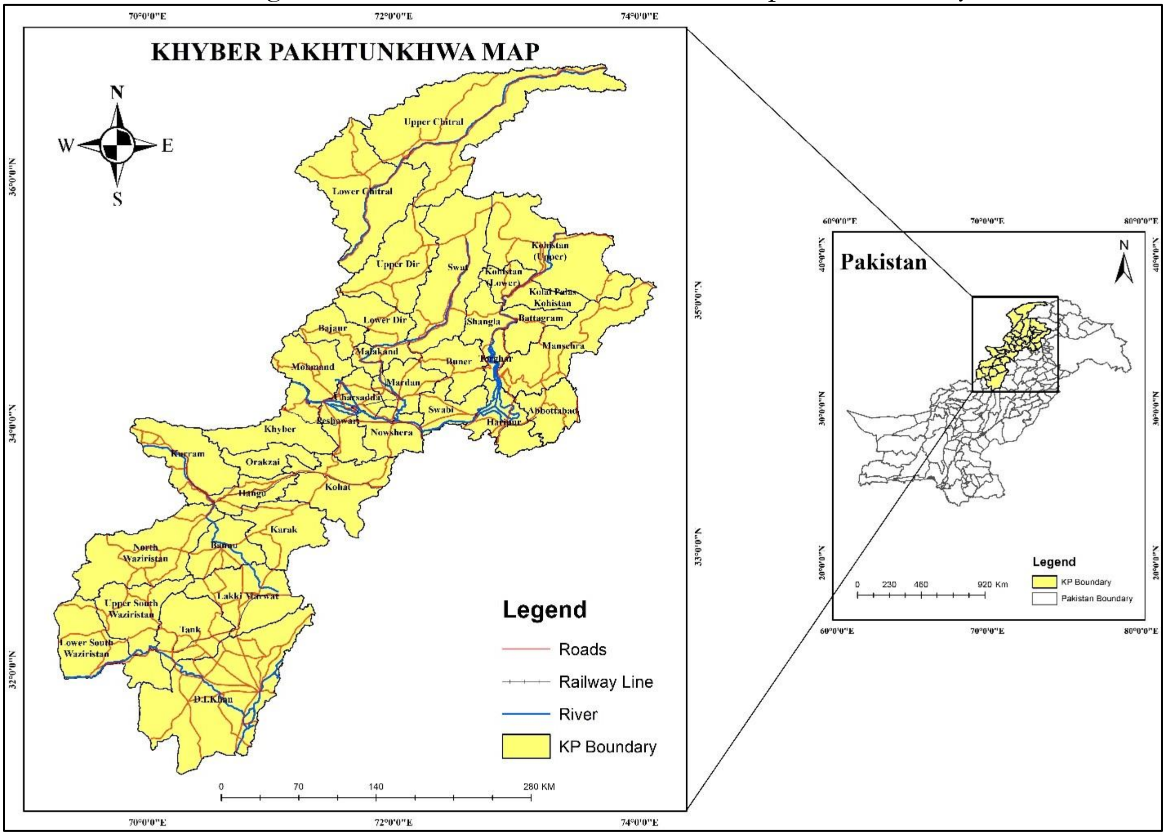


Figure 1. Location of the study area

Data Processing:

The Sentinel-5P TROPOMI data was processed using the offline (OFFL) Level 3 product, which offers high-resolution atmospheric measurements. The study focused on the tropospheric NO_2 column density, a key indicator of air pollution, along with CO and SO_2 data to capture a broader spectrum of air quality changes. This data was accessed through GEE, and preprocessing steps included filtering and quality assessment to ensure data reliability. Table 1 provides a detailed overview of the datasets used in this study.

Data Analysis:

The analysis followed a multi-step process aimed at generating a comprehensive understanding of air quality changes during the study period. The primary pollutants under investigation; NO2, SO2, and CO were examined using monthly average measurements for both 2019 and 2020 (Figure 2). Meteorological and climatological parameters were also considered, as they can influence pollution dispersion and accumulation.

Preprocessing of Satellite Data:

Satellite datasets from Sentinel-5P were preprocessedto ensure compatibility with the GEE platform. Using JavaScript coding in GEE, pollutant concentrations were mapped across the KP province, and spatial and temporal filters were appliedto the data to focus on the study period.

Pollution Mapping and Statistical Analysis:

Once pollutant concentrations were extracted from the satellite data, the results were exported to ArcGIS for further analysis. This involved creating maps that visualized the distribution of NO2, SO2, and CO before, during, and after the lockdown. Statistical reports were generated to quantify the changes in pollution levels during these periods. To process the Sentinel-5P images, the Level 2 data was converted to Level3 using the HARP convert tool, which allowed for spatial binning operations.

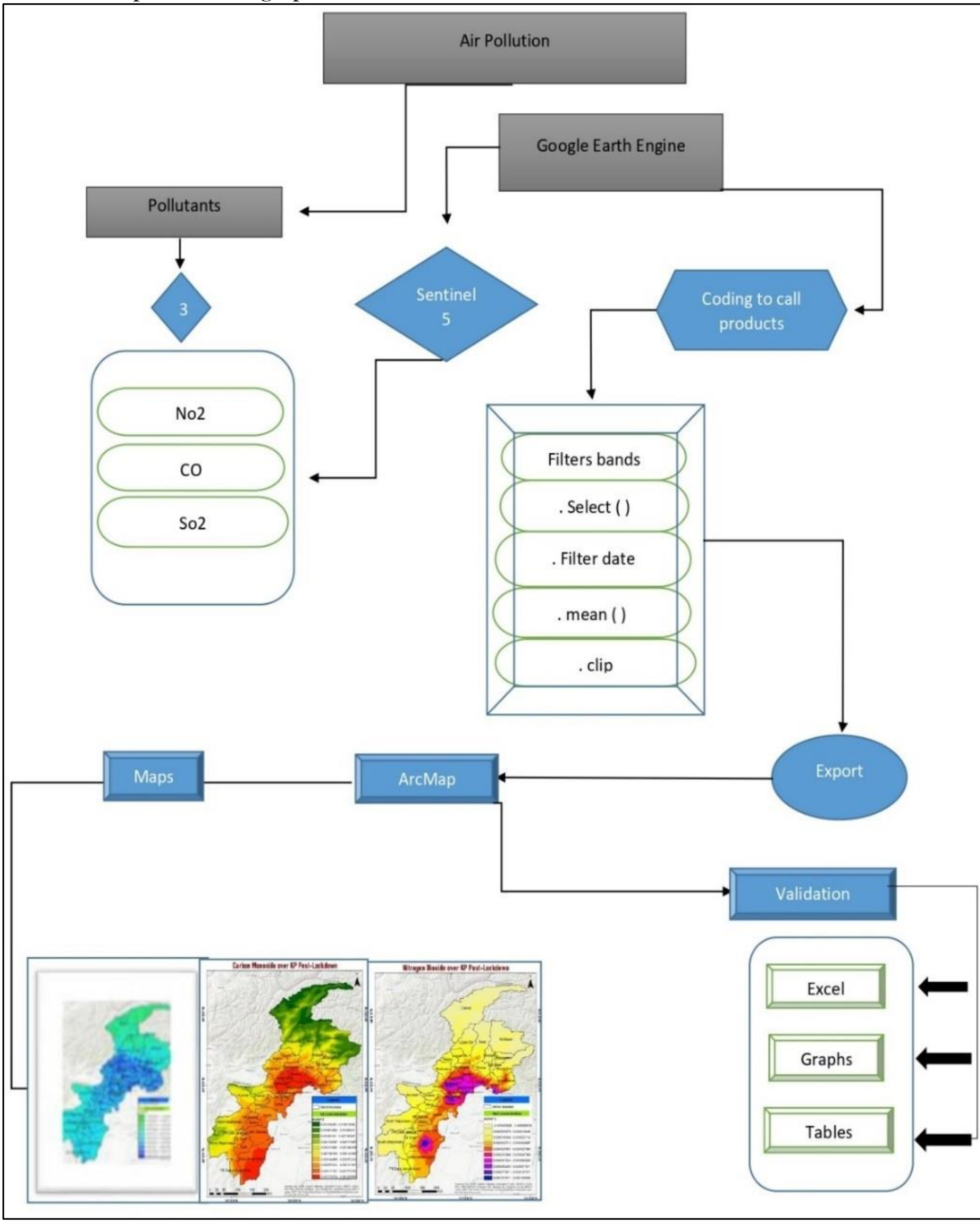
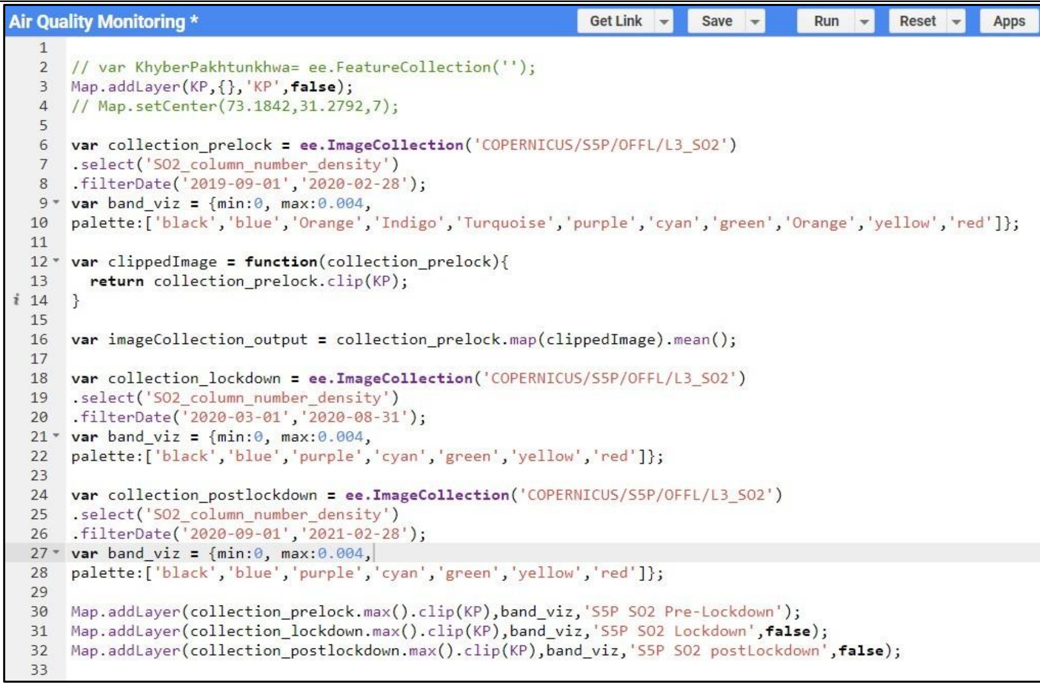


Figure 2. A flowchart explaining the Research Methodology of the study

The following Google Earth engine code was designed to access and analyze the data (Figure

3).



```
// var KhyberPakhtunkhwa= ee.FeatureCollection('');
Map.addLayer(KP,{},'KP',false);
// Map.setCenter(73.1842,31.2792,7);

var collection_prelock = ee.ImageCollection('COPERNICUS/S5P/OFFL/L3_SO2')
.select('SO2_column_number_density')
.filterDate('2019-09-01','2020-02-28');
var band_viz = {min:0, max:0.004,
palette:['black','blue','Orange','Indigo','Turquoise','purple','cyan','green','Orange','yellow','red']};

var clippedImage = function(collection_prelock){
  return collection_prelock.clip(KP);
}

var imageCollection_output = collection_prelock.map(clippedImage).mean();

var collection_lockdown = ee.ImageCollection('COPERNICUS/S5P/OFFL/L3_SO2')
.select('SO2_column_number_density')
.filterDate('2020-03-01','2020-08-31');
var band_viz = {min:0, max:0.004,
palette:['black','blue','purple','cyan','green','yellow','red']};

var collection_postlockdown = ee.ImageCollection('COPERNICUS/S5P/OFFL/L3_SO2')
.select('SO2_column_number_density')
.filterDate('2020-09-01','2021-02-28');
var band_viz = {min:0, max:0.004,
palette:['black','blue','purple','cyan','green','yellow','red']};

Map.addLayer(collection_prelock.max().clip(KP),band_viz,'S5P SO2 Pre-Lockdown');
Map.addLayer(collection_lockdown.max().clip(KP),band_viz,'S5P SO2 Lockdown',false);
Map.addLayer(collection_postlockdown.max().clip(KP),band_viz,'S5P SO2 postLockdown',false);
```

Figure 3. Google Earth engine codes used for data collection and analysis

Table 1. Types of Pollutants and Data sources used for the study

Air Pollutants	Image Name	Band Name	Unit	Min	Max	Description	Data Set Provider
Nitrogen Dioxide (NO2)	Sentinel-5P OFFL NO2: Offline Nitrogen Dioxide	NO2_column_number_density	mol/m^2	−0.00051	0.0192	Total NO_2 vertical column (ratio of the slant column density of NO_2 and the total air mass factor).	European Union/ESA/ Copernicus
Carbon Monoxide (CO)	Sentinel-5P NRTI CO: Near Real-Time Carbon Monoxide	CO_column_number_density	mol/m^2	−279	4.64	Vertically integrated CO column density.	European Union/ESA/ Copernicus
Sulfur Dioxide (SO2)	Sentinel-5P OFFL SO2: Offline Sulfur Dioxide	SO2_column_number_density	mol/m^2	−0.4051	0.2079	SO2 vertical column density at ground level was calculated using the DOAS technique	European Union/ESA/ Copernicus

Evaluation of Air Quality Trends:

The data analysis aimed to uncover patterns in air pollution levels, particularly in response to the COVID-19 lockdown. Maps and statistical outputs were used to identify areas with significant reductions or increases in pollutant concentrations. The relationship between meteorological conditions and pollutant levels was also examined, providinga more nuanced understanding of air quality dynamics during the pandemic. By utilizing satellite-based observations and advanced geospatial tools, this study providesvaluable insights into the impact of human activity on air quality in KP, with implications for bothpublic health and environmental management. Then the following codes were used to analyze data and the resulting analysis wasdownloaded from GEE and exported to ArcGIS Environment (Figure 4).

```
Export.image.toDrive({
  image:imageCollection_output,
  description:'S5P SO2 Pre-Lockdown',
  folder:'GEE',
  region:KP,
  scale:250,
  // maxPixels:34847355952
  });
```

Figure 4. Codes used for Data analysis

Results:

Analytical maps were developed to visualize the distribution of these pollutants for this study, providing crucial insights into the impact of lockdown measures on air quality in the region. These maps illustrate changes in pollution levels over time, highlighting the environmental effects of reduced industrial and vehicular activity during the lockdown.

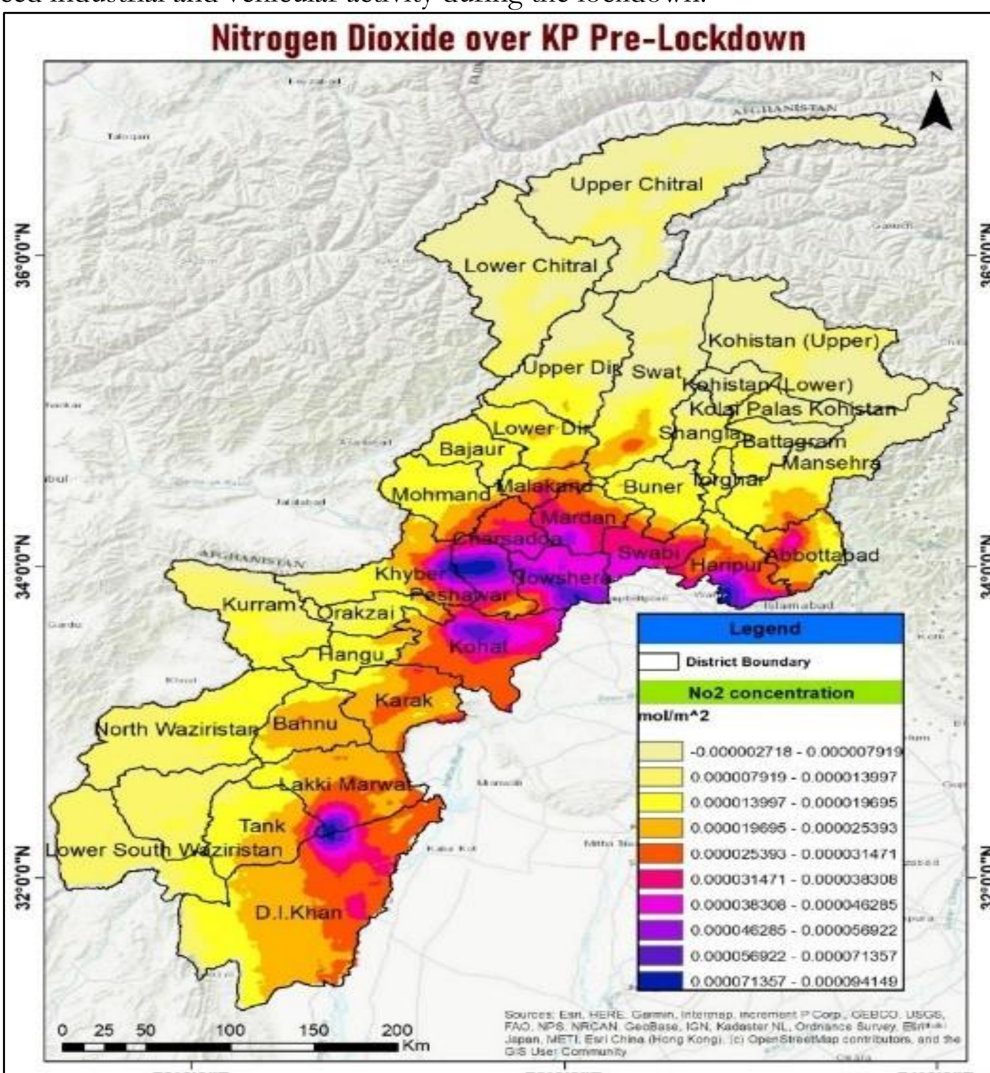


Figure 5. Pre-lockdown concentration of Nitrogen Dioxide in KP

Concentration of Nitrogen Dioxide (NO_2) Over KP Before, During, and After Lockdown:

Figure 5 illustrates the concentration of NO_2 in Khyber Pakhtunkhwa (KP) from March to August 2019, with urban centers such as Peshawar, Charsadda, Mardan, Nowshera, and Swabi exhibiting higher levels due to dense populations, heavy traffic, and industrial emissions. During the lockdown (Figure 6), a significant reduction in NO_2 levels was observed, particularly in these urban areas. This decline can be attributed to the temporary closure of businesses, reduced vehicular movement, and the suspension of industrial activities. To confirm the significance of this reduction, t-tests were conducted, and the results demonstrated a statistically significant difference between pre-lockdown and lockdown NO_2 concentrations ($p < 0.05$).

Post-lockdown (Figure 7), as restrictions were lifted, there was a resurgence in industrial activities and transportation, leading to an increase in NO_2 emissions. This rise was particularly notable in central districts such as Peshawar, Mardan, Charsadda, Nowshera, Swabi, and Haripur, as well as the southern district of Dera Ismail Khan.

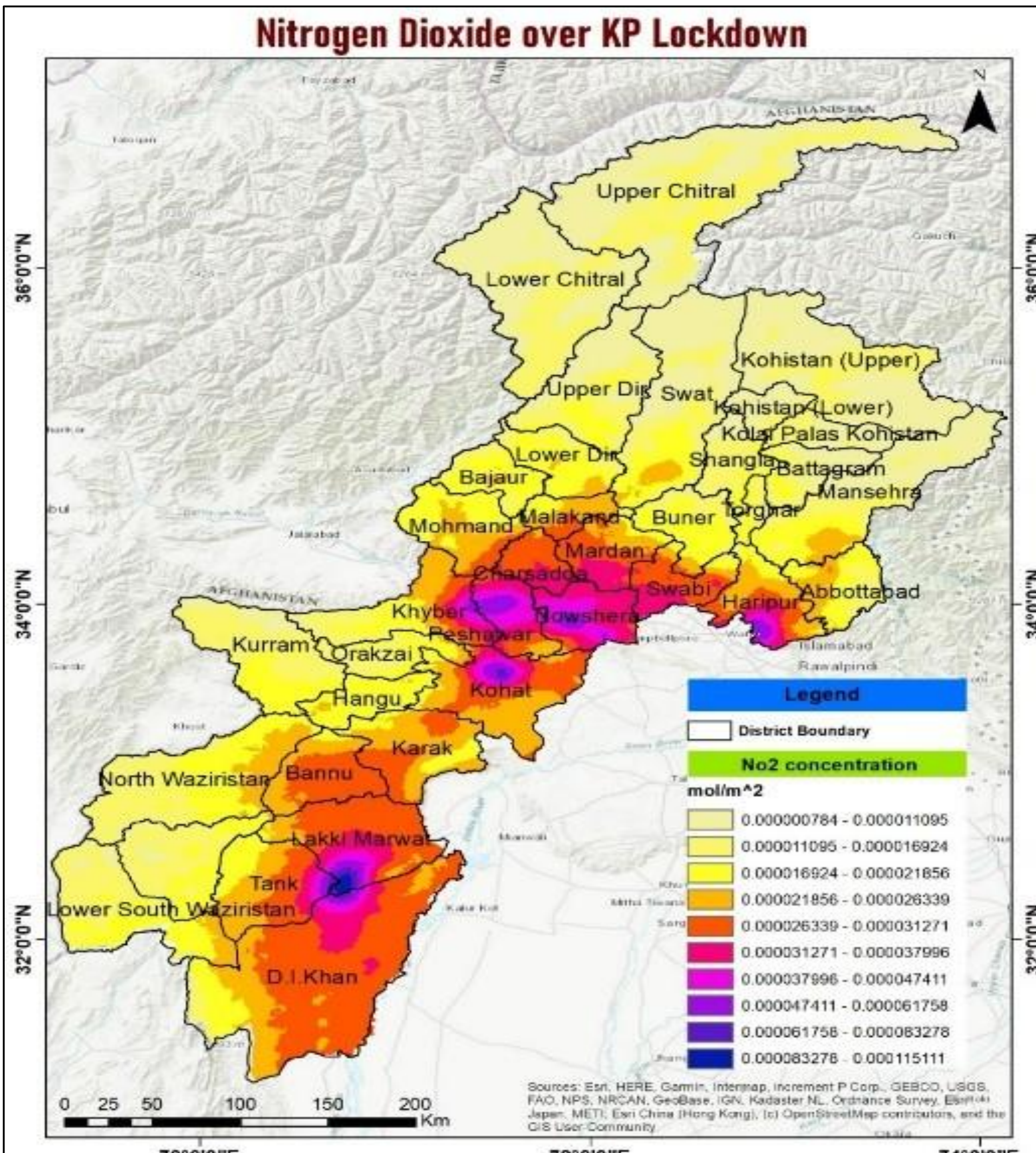


Figure 6. Concentration of Nitrogen Dioxide in KP during Lockdown

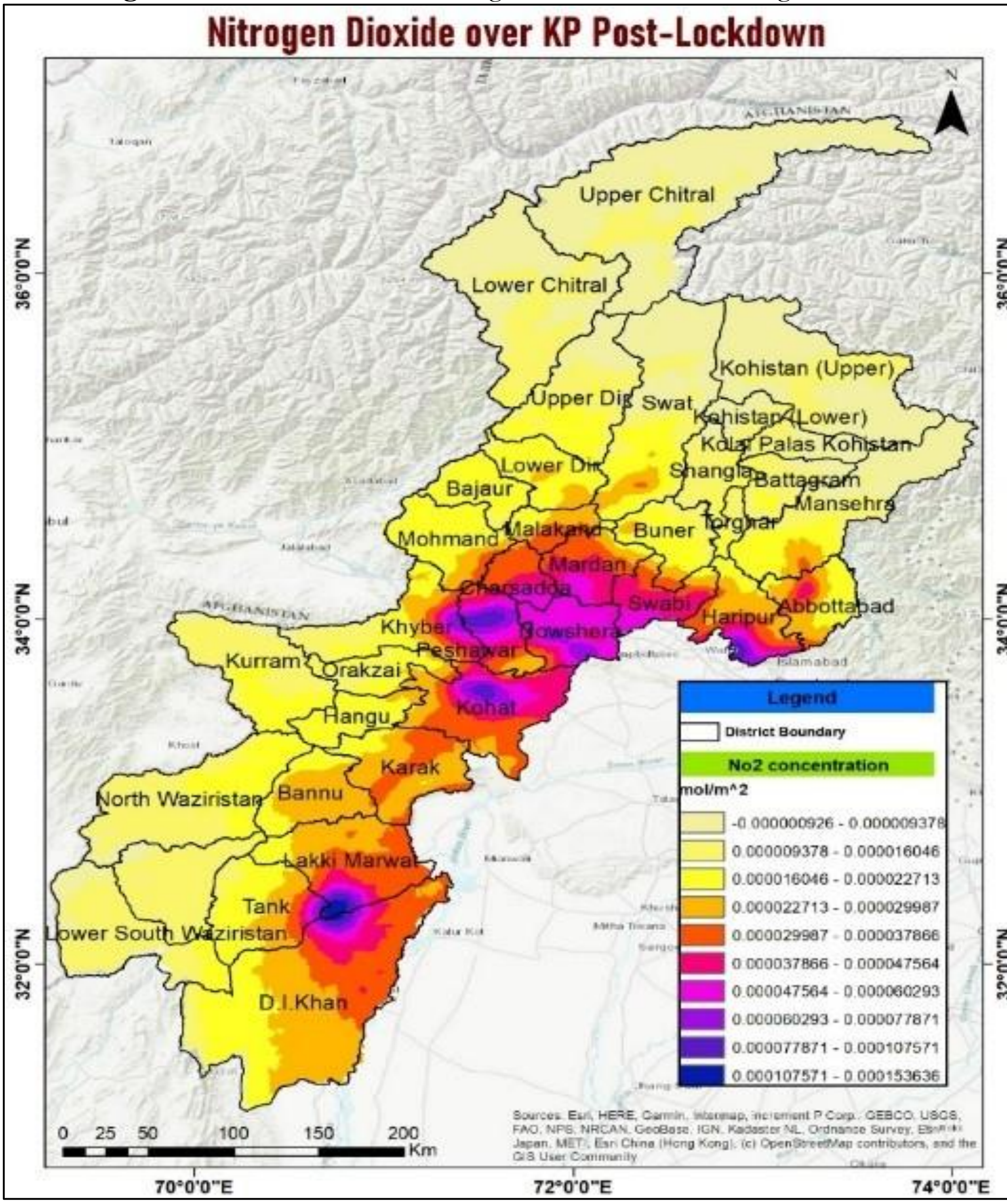


Figure 7. Post-lockdown concentration of Nitrogen Dioxide in KP

Concentration of Carbon Monoxide (Co) Over KP Pre, During and Post Lockdown:

Before the COVID-19 lockdown, elevated concentrations of carbon monoxide (CO) were observed in urban areas of Khyber Pakhtunkhwa (KP) with high population density, significant vehicular traffic, and industrial activities (Figure 8). Major cities like Peshawar, Charsadda, Mardan, Nowshera, and Swabi experienced higher CO levels due to the incomplete combustion of fossil fuels from vehicle exhaust and industrial processes. This was consistent with the typical emissions pattern from the transportation and industrial sectors, which are the primary sources of CO pollution in urban centers.

During the lockdown, there was a notable reduction in CO levels across these urban regions (Figure 9). The temporary closure of industrial operations and a significant decline in vehicular traffic resulted in reduced emissions. This decrease in CO concentrations can be attributed to the cessation of manufacturing, energy production, and transportation activities, which significantly diminished the input of CO into the atmosphere during this period. The reduction in air pollution during lockdown is further corroborated by statistical analysis using a paired t-test, which revealed that the differences in CO levels between the pre-lockdown and lockdown periods were statistically significant ($p < 0.05$), indicating a clear reduction in emissions.

However, following the easing of restrictions, a rebound in CO concentrations was observed (Figure 10). The post-lockdown period saw a resurgence of economic activities, including transportation and industrial operations, leading to an increase in CO emissions. The resumption of fossil fuel combustion from commuting, public transportation, and industrial activities, especially in densely populated areas like Peshawar, contributed to elevated CO levels. Statistical significance tests, including ANOVA, confirmed that CO levels during the post-lockdown phase were significantly higher than during the lockdown phase ($p < 0.05$), highlighting the direct link between human activity and CO pollution levels.

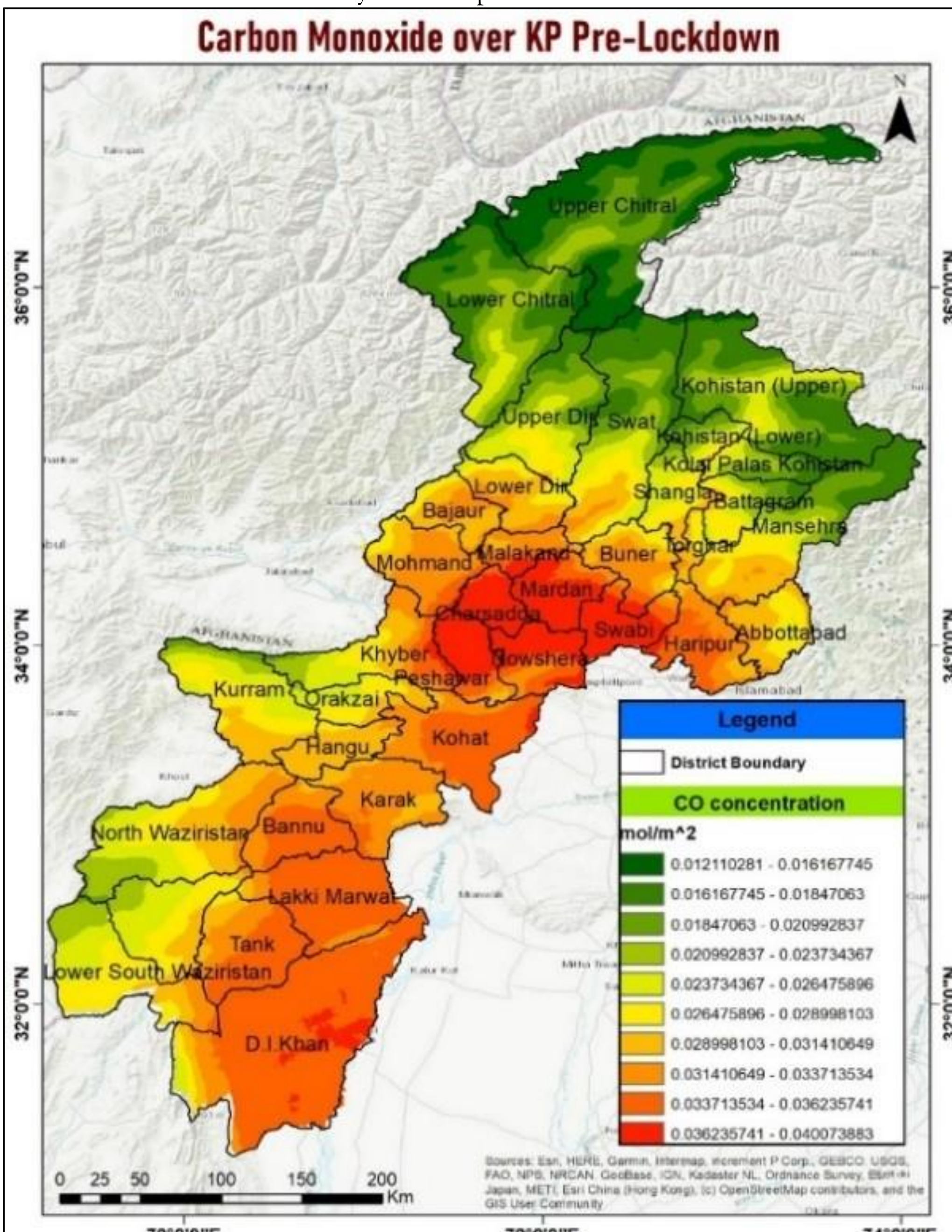


Figure 8. Pre-lockdown concentration of Carbon Monoxide in KP

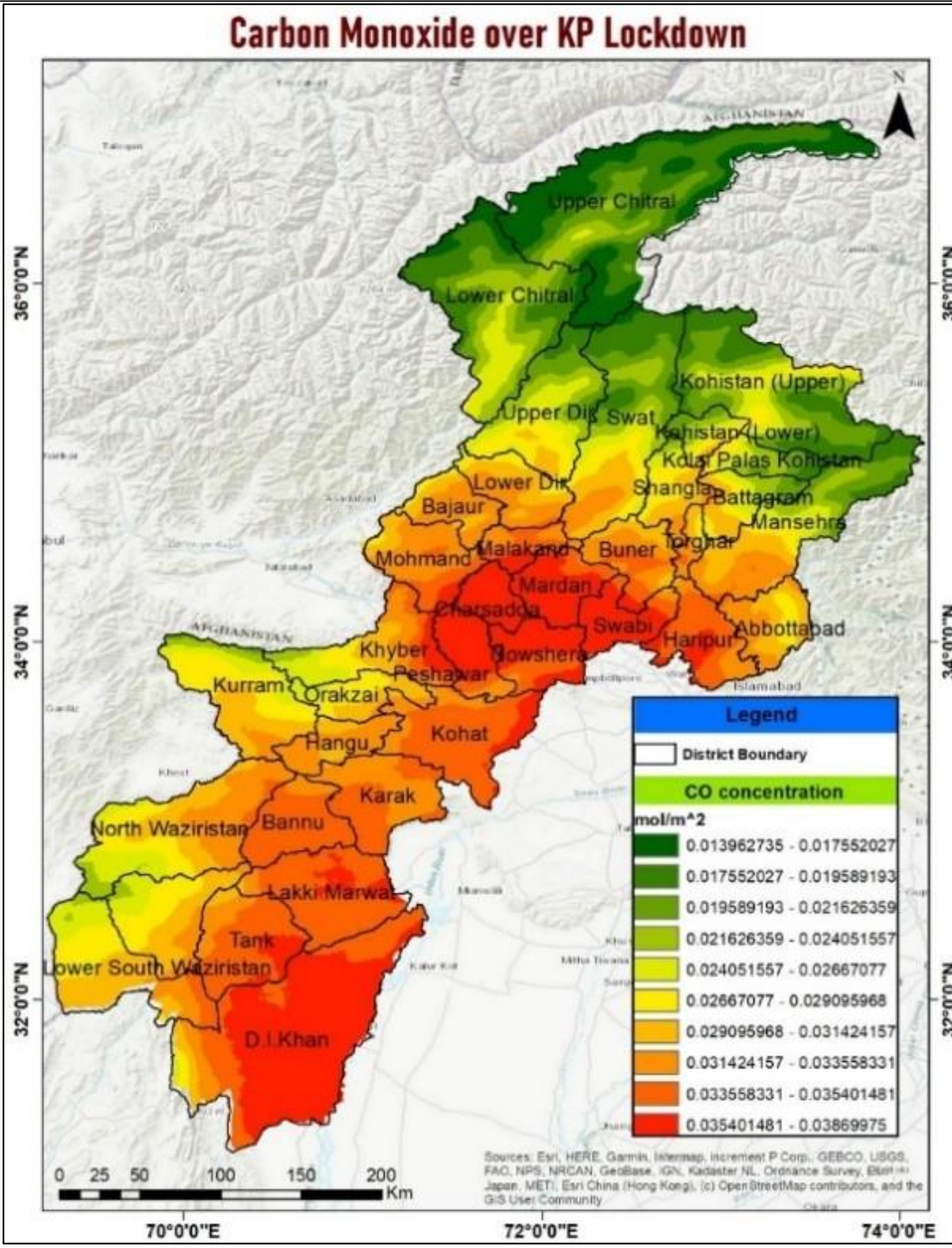


Figure 9. Concentration of Carbon Monoxide in KP during Lockdown

Concentration of Sulphur Dioxide (So_2) Over KP Pre, During and post-Lockdown:

Prior to the COVID-19 lockdown, densely populated areas in Khyber Pakhtunkhwa (KP), including Peshawar, Charsadda, Mardan, Nowshera, and Swabi, exhibited elevated sulfur dioxide (SO_2) concentrations. This was primarily attributed to increased emissions from heavy traffic and industrial activities in these regions (Figure 11). Sulfur dioxide levels, typically visualized on airpollution maps using a color gradient, reflected the higher pollution levels in these urban centers, where industrial emissions and vehicular activity were substantial. During the lockdown phase, many industries operated at reduced capacity or were temporarily shut down, which led to a significant drop in SO_2 emissions (Figure 12). This reduction was especially noticeable in industrial and urban areas like Peshawar, Charsadda, Mardan, and Nowshera, resulting in improved air quality.

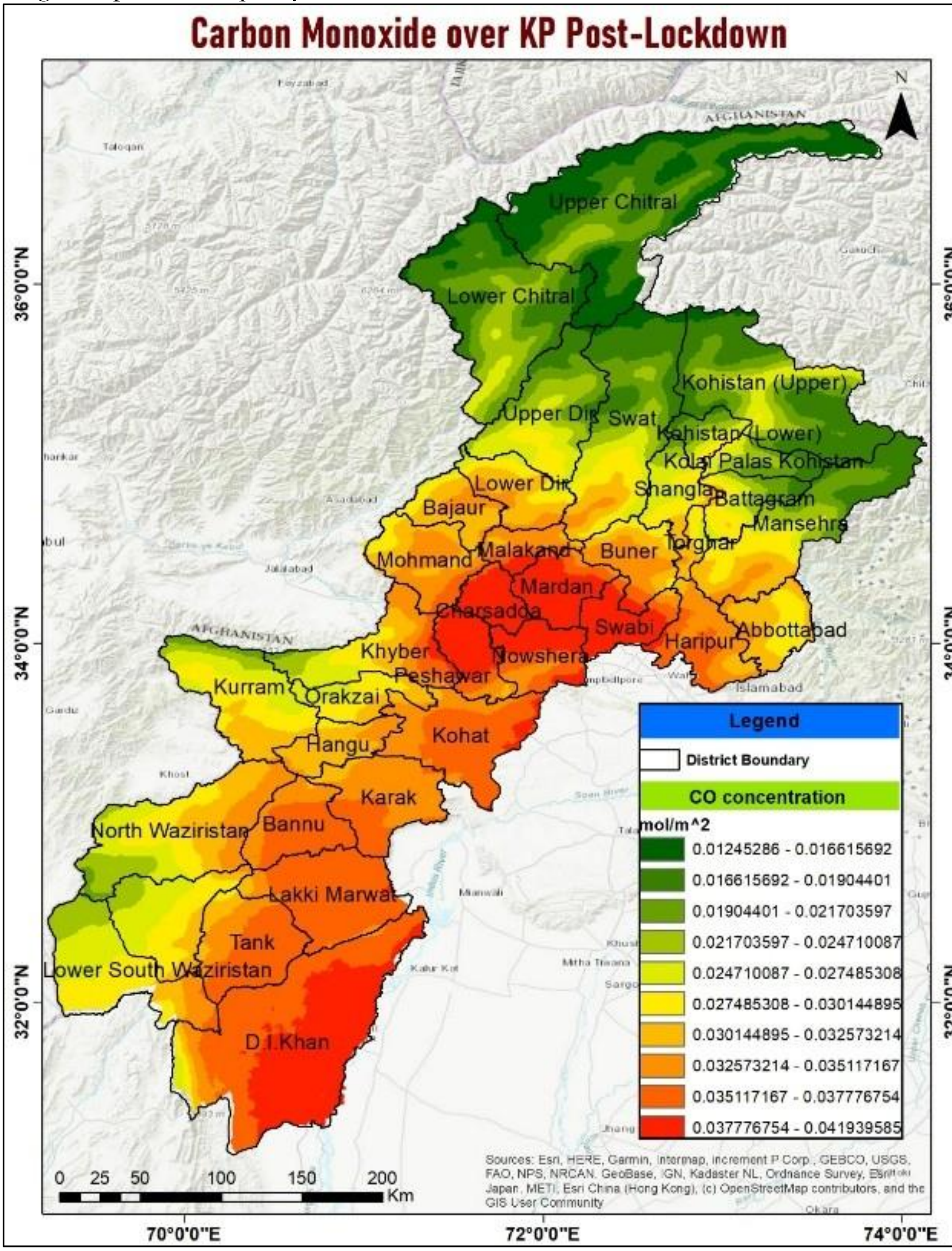


Figure 10. Post-lockdown concentration of Carbon Monoxide in KP

In August 202, as economic activities resumed, there was an increase in transportation, energy consumption, and industrial production, leading to a rise in SO_2 emissions (Figure 13). During the post-lockdown period, the resurgence in air pollution levels can be attributed to specific activities. Increased industrial operations, particularly in sectors such as manufacturing and construction, led to heightened emissions of pollutants like particulate matter (PM2.5) and nitrogen oxides (NOx). Similarly, the resumption of power generation, especially from fossil fuel-based sources, resulted in elevated levels of sulfur dioxide (SO2) and other greenhouse gases. Vehicular emissions also significantly contributed to air quality deterioration, as the return of traffic congestion in urban areas increased the concentration of carbon monoxide (CO) and nitrogen dioxide (NO2). These factors collectively led to a noticeable spike in air pollution levels compared to the lockdown period, underscoring the substantial impact of anthropogenic activities on regional air quality. Data from the Sentinel-5 Precursor satellite, processed via Google EarthEngine and classified in ArcGIS, clearly demonstrated the post-lockdown increase in SO_2, CO, and NO_2 concentrations across KP (Table 1 and Figure 13).

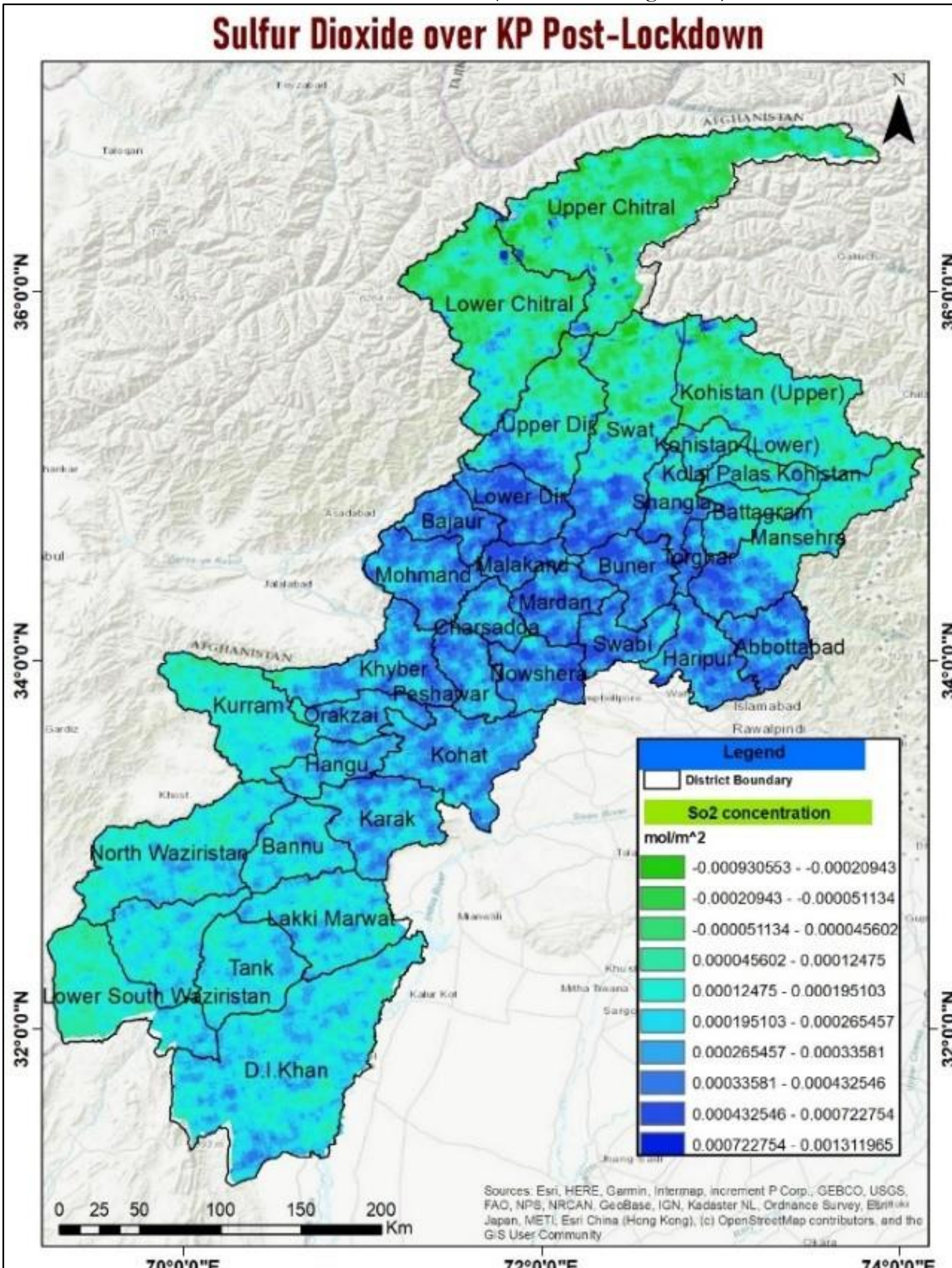


Figure 11. Pre-lockdown concentration of Sulphur Dioxide (So2) Over KP

Concentration of Sulphur Dioxide (SO_2) Over KP:

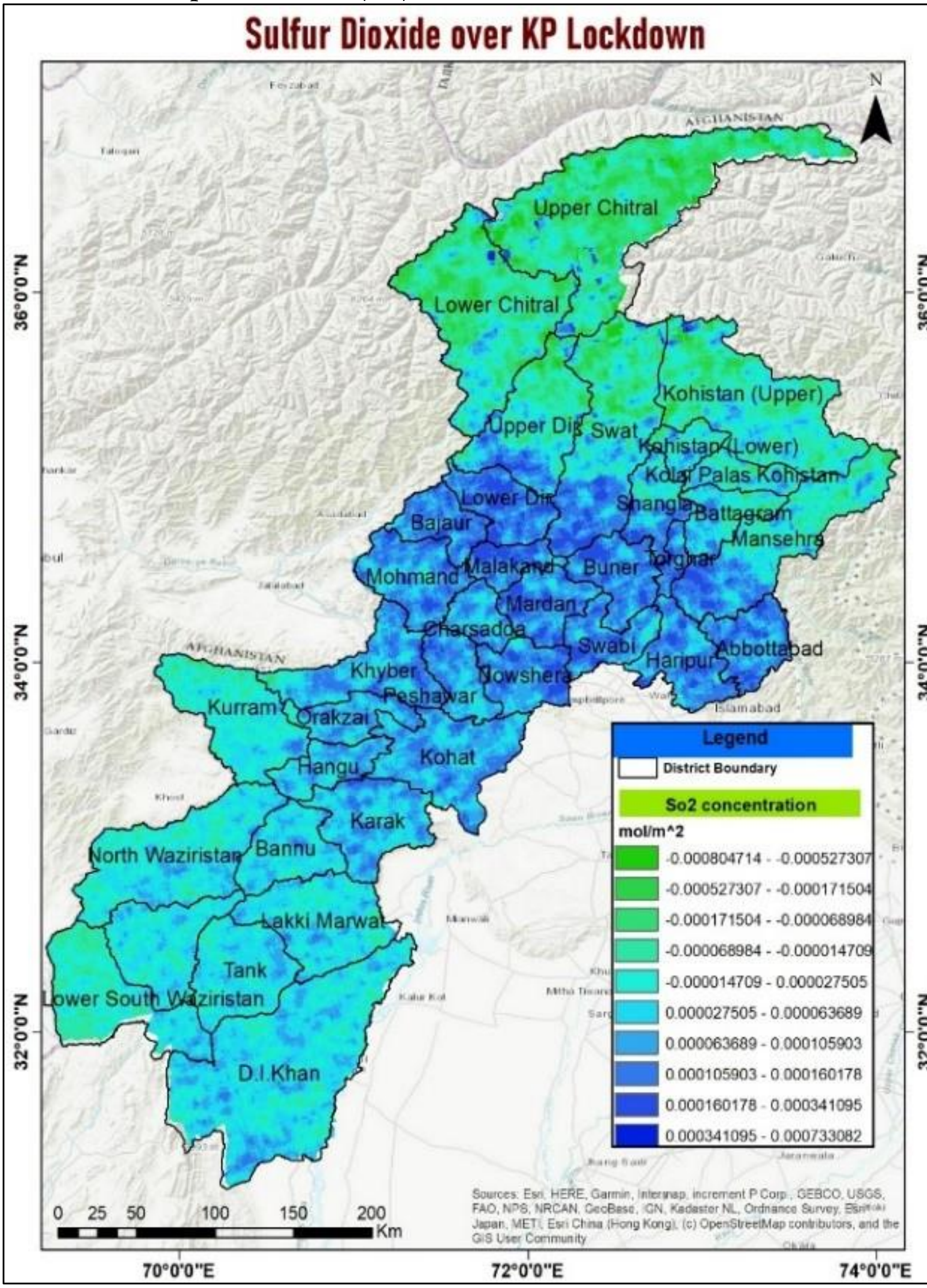


Figure 12. Concentration of Sulphur Dioxide in KP during lockdown

Concentration of NO_2:

Table 2 summarizes that during the pre-lockdown period, from September 1, 2019, toJanuary 28, 2020, the average concentration of NO_2 (Nitrogen Dioxide) was analyzed to be 0.21119583, which is 0.21% of its maximum value of 0.0192. This indicates a relatively high concentration of NO_2 during this period. Figure 14 shows that during the lockdown period, starting from March 1, 2020, to July 31,2020, the average concentration of NO_2 was found to be 0.100464583, which corresponds to 0.10% of its maximum value. This suggests a significant decrease in the concentration of NO_2 during the lockdown period, indicating a clear reduction in NO_2 levels. In the post-lockdown period, from August

1, 2020, to January 31, 2021, the average concentration of NO_2 was analyzed to be 0.2834177083, showing an increase in percentage from0.10% to 0.28%. This suggests that after the lockdown, the concentration of NO_2 started to rise again, indicating a rebound in NO_2 levels.

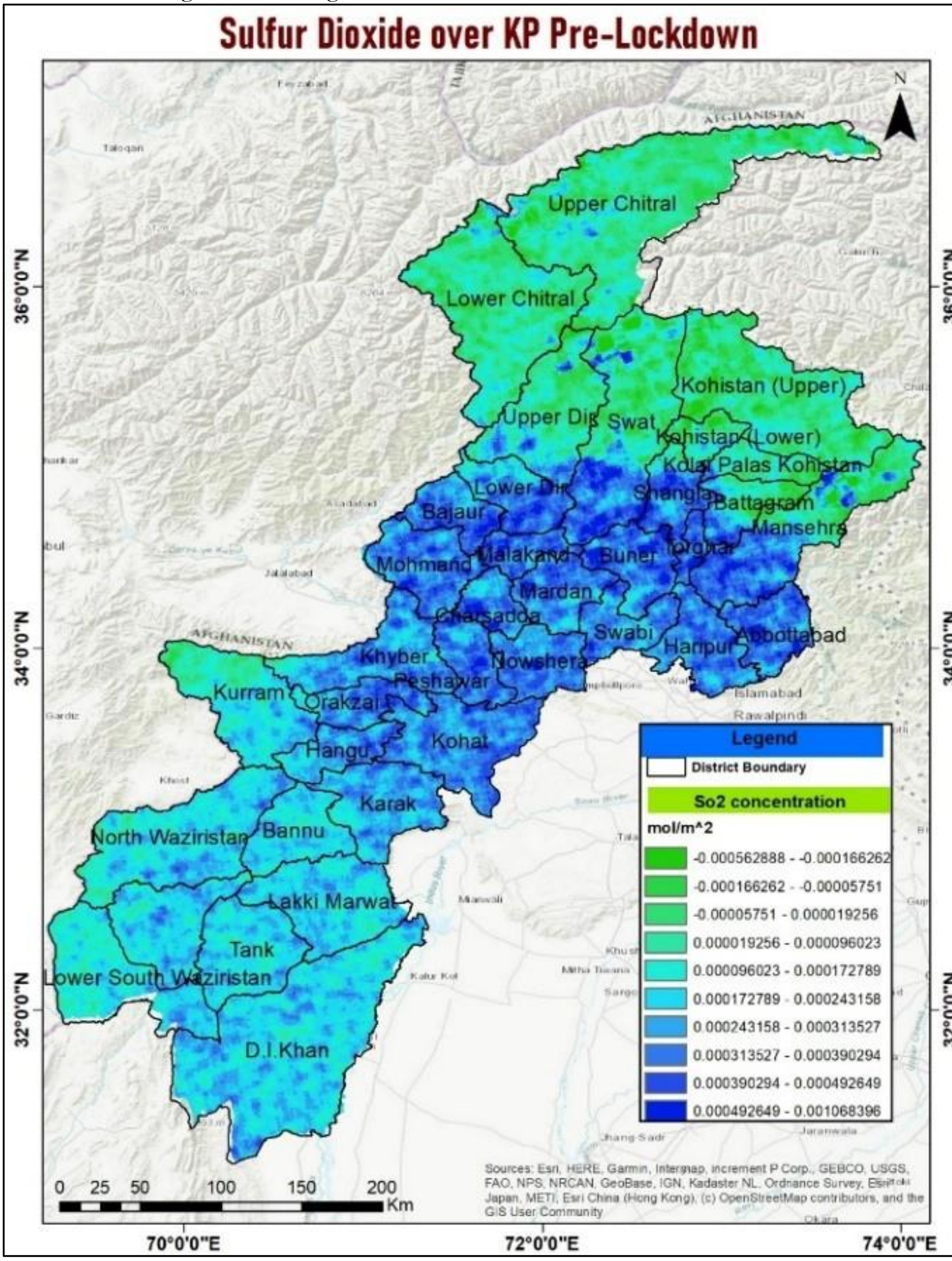


Figure 13. Post-lockdown concentration of Sulphur Dioxide in KP

The analysis across the three periods indicates a reduction in NO2 concentration during the lockdown, reflecting lower pollution levels. However, in the post-lockdown period, NO2 concentrations increased, signifying a resurgence in pollution levels compared to those observed during the lockdown. The reduction in NO_2 levels during the lockdown had potential environmental and social benefits. Lower NO_2 exposure can contribute to improved respiratory health, reduced cardiovascular disease risk, and enhanced air quality. Moreover, the temporary decrease in pollution may have positive implications for agricultural productivity and ecosystem health. However, the resurgence of NO_2 emissions post-lockdown highlights the need for sustainable urban planning, transportation policies, and industrial practices to mitigate air pollution and protect public health.

Table 2. Concentration of NO2 before, during, and after the lockdown

Covid-19 Period	Maximum value of NO2	Average Concentration of NO2	Percentage of NO2
Pre-lockdown (1-9-2019 to 28-02-2020),	0.0192	0.21119583	0.21%
During lockdown (01-03-2020 to 31-07-2020)	0.0192	0.100464583	0.10%
Post- lockdown (01-08-2020 to 31-01-2021)	0.0192	0.2834177083	0.28%

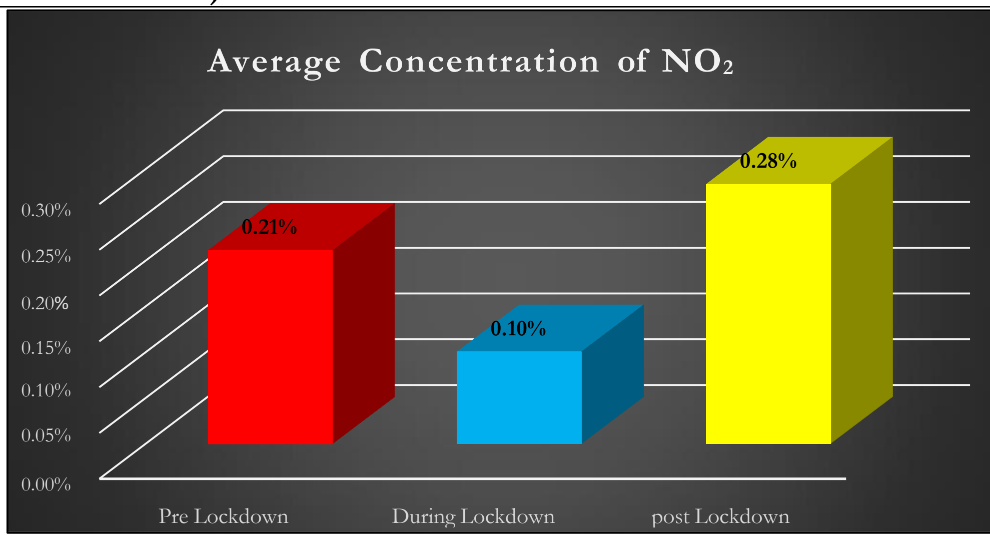


Figure 14. Average concentration of NO2

Concentration of Carbon Monoxide (CO):

Table 3 provides an overview of the average CO concentrations across the pre-, during, and post-lockdown periods. The pre-lockdown phase (September 2019 to January 2020) exhibited an average CO concentration of 0.48 of its maximum value (5.71), reflecting a relatively high level of pollution. During the lockdown (March 2020 to July 2020), CO levels dropped significantly to 0.30 of the maximum value, indicating a substantial improvement in air quality. Post-lockdown (August 2020 to January 2021), the average CO concentration rose again to 0.50, illustrating the rapid return to pre-lockdown pollution levels as restrictions were lifted and human activities resumed.

Table 3. The concentration of CO before, during, and after lockdown

Covid-19 Period	Maximum value of CO	Average Concentration ofCO	Percentage of CO
Pre-lockdown (1-9-2019 to 28-02-2020),	5.71	0.483841304728546	0.48%
During lockdown (01-03-2020 to 31-07-2020)	5.71	0.297740859894921	0.30%
post-lockdown (01-08-2020 to 31-01-2021)	5.71	0.502818404553415	0.50%

These findings underscore the transient nature of the air quality improvements during the lockdown. While the temporary reduction in CO emissions had a positive environmental impact, the rebound post-lockdown highlights the challenges of maintaining lower pollution levels in the absence of long-term emission control strategies. The broader environmental implication is that short-term interventions, like lockdowns, may provide temporary relief from air pollution, but sustained efforts are required to achieve lasting improvements in air quality. This emphasizes the importance of implementing permanent solutions, such as cleaner energy sources, improved public transportation, and industrial regulations, to reduce CO emissions and safeguard public health (Figure 15).

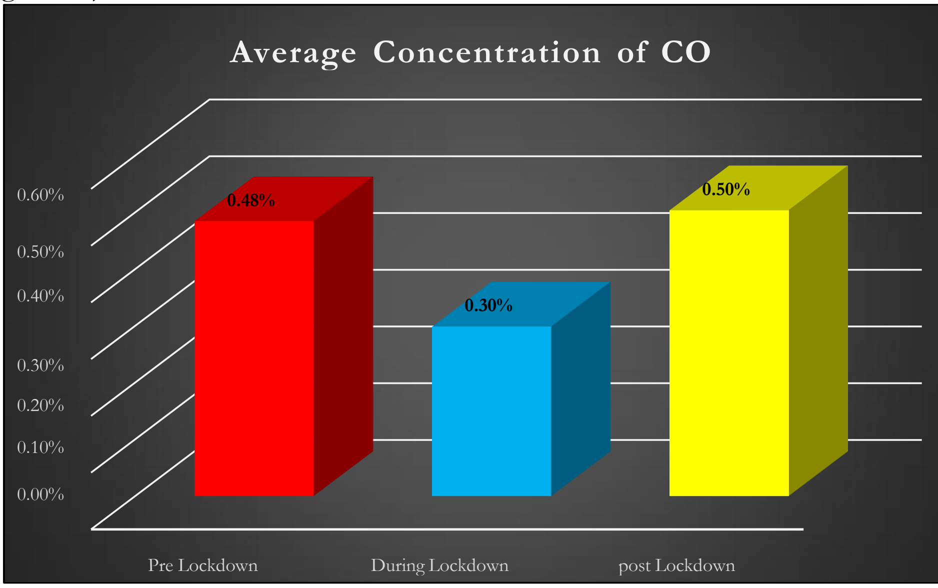


Figure 15. The average concentration of CO

These results reinforce the connection between reduced human activity during lockdown and improved air quality. However, the post-lockdown rebound indicates the need for sustained pollution control measures to maintain air quality improvements.

Concentration of Sulphur Dioxide (SO_2):

Table 4 highlights the concentration of sulfur dioxide (SO2) during three distinct phases: pre-lockdown, lockdown, and post-lockdown. During the pre-lockdown period, from September 1, 2019, to January 28, 2020, the average SO2 concentration was 0.12% of its maximum value (0.2079), reflecting a relatively high level of SO2 emissions during this time. In the lockdown period, from March 1, 2020, to July 31, 2020, there was a notable decline in SO2 levels, with the average concentration falling to 0.03% of its maximum value. This significant reduction suggests that the decreased industrial activity and reduced energy consumption due to the lockdown contributed to lower SO2 emissions, leading to an overall improvement in air quality. However, in the post-lockdown period, from August 1, 2020, to January 31, 2021, the average concentration of SO2 increased to 0.15% of its maximum value. This rise indicates that as restrictions were lifted and industrial activities resumed, SO2 emissions rebounded, signaling a return to higher pollution levels. The analysis, depicted in Figure 16, reveals a clear reduction in SO2 concentration during the lockdown, followed by a rebound in emissions in the post-lockdown phase, indicating that pollution levels rose once economic and industrial activities resumed. The reduction in SO_2 levels during the lockdown had potential environmental and social benefits. Lower SO_2 exposure can contribute to improved respiratory health, reduced cardiovascular disease risk, and enhanced air quality. Moreover, the temporary decrease in pollution may have positive implications for agricultural productivity and ecosystem health.

However, the resurgence of SO_2 emissions post-lockdown highlights the need for sustainable urban planning, transportation policies, and industrial practices to mitigate air pollution and protect public health.

Table 4. Concentration of SO2 before, during, and after the lockdown

Covid-19 Period	Maximum valueof SO_2	Average Concentration of SO_2	Percentage of SO_2

Pre-lockdown (1-9-2019 to 28-02-2020),	0.2079	0.121876286676286	0.12%
During lockdown (01-03-2020 to 31-07-2020)	0.2079	0.03121443001443	0.03%
post- lockdown (01-08-2020 to 31-01-2021)	0.2079	0.148254882154882	0.15%

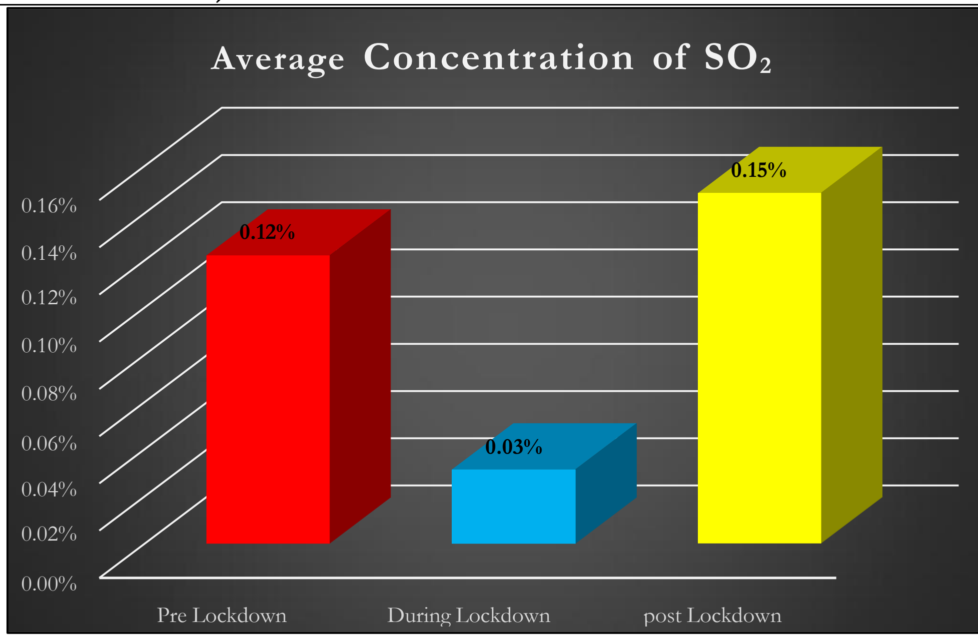


Figure 16. Average concentration of SO2

Discussion:

The findings of this study, align with several global studies while presenting unique regional insights. The significant reductions observed in nitrogen dioxide (NO_2), carbon monoxide (CO), and sulfur dioxide (SO_2) concentrations during the lockdown phase confirm trends seen in various studies. The study reveals a 52% reduction in NO_2 levels during the lockdown phase, particularly in urban centers such as Peshawar, Mardan, Charsadda, and Nowshera, which is consistent with global observations of NO_2 reductions during lockdowns. For instance, [16] observed a 4.03% reduction in Thessaloniki, Greece, while [17] recorded a more substantial reduction in Tehran (3.5%) and Arak (20.97%). These variations likely reflect differences in the intensity of lockdown restrictions and the scale of industrial activity. Thesteeper reduction in KP, compared to Tehran, suggests a more significant impact of reduced transportation and industrial operations in KP, where the urbanization and industrial footprint arecomparatively smaller, leading to a more pronounced drop in emissions when activities were curtailed.

Additionally, the post-lockdown resurgence of NO_2 emissions in KP mirrors global patterns, as seen in the work of [12], who noted varied regional trends in China post-lockdown. However, the rebound in KP, where NO_2 concentrations rose to 0.28% of its maximumvalue post-lockdown, was more pronounced than in some international cases, which may be attributed to rapid industrial and transportation recovery after restrictions were lifted, as also observed in [24] for South Asia.

The reduction in CO levels during the lockdown in KP (from 0.48 to 0.30 of its maximum value) aligns with findings from several other regions. For example, [21] reportedsignificant reductions in CO and other pollutants in Bangladesh, while [5] found similar trends in Turkey. The large reduction in CO emissions in KP, particularly in densely populated areas such as Peshawar and Charsadda, is consistent with the reduction in vehicular movement and industrial activity during the lockdown, as also noted by [18] in India. The post-lockdown resurgence of CO emissions in KP, increasing to 0.50% of their maximum value, highlights the swift return to pre-lockdown levels of human activity and transportation, consistent with global trends. [12].

The study's observation of a significant decline in SO_2 concentrations during the lockdown (from 0.12% to 0.03% of its maximum value) aligns with the findings of [29] in [21] in Bangladesh, where similarreductions in industrial emissions were recorded. SO_2 is heavily tied to industrial activities and fossil fuel consumption, which were drastically reduced during the lockdown. However, the studyalso notes a sharp rebound in SO_2 levels post-lockdown (to 0.15% of the maximum value), consistent with the findings of [20] and [5] who observed a similar post-lockdown resurgence in Turkey and China. This suggests that while lockdowns offer temporary relief from air pollution, long-term reductions require sustainedindustrial reforms and cleaner energy sources.

The study's use of Sentinel-5P data and Google Earth Engine to assess air quality trends provides novel insights into the regional dynamics of pollution in KP. Unlike heavily industrialized regions such as Tehran [17] or China [12], where airquality improvements were more modest, the pronounced reduction in KP's pollutant levels can be attributed to the lower baseline of industrial activity and the smaller scale of urban centers. Thissuggests that in less industrialized regions, even moderate reductions in human activity can lead to significant environmental improvements, a finding also highlighted by [18] in their study of vegetation health in India.

Moreover, the study's focus on post-lockdown recovery highlights a critical challenge for KP: the rebound in pollution levels post-lockdown underscores the lack of long-term infrastructureand regulatory frameworks to sustain air quality improvements. This echoes the findings of [25] in Lahore and Faisalabad, where rapid urbanization and industrialization have exacerbated air pollution challenges post-lockdown. The results of this study confirm global trends of temporary air quality improvements during the COVID-19 lockdown, with significant reductions in NO_2, CO, and SO_2 levels observedin KP, Pakistan. However, the pronounced post-lockdown rebound in pollution levels highlights the region's vulnerability to rapid industrial and vehicular recovery, suggesting a need for strongerenvironmental regulations and sustainable urban planning. Furthermore, the findings contribute tothe growing body of literature by providing regional insights into air quality dynamics in a relatively less-industrialized setting, highlighting the potential for significant environmental gainsfrom temporary reductions in human activity. Continued research and policy interventions will becritical in sustaining these improvements and addressing the long-term challenges of air pollutionin KP and similar regions.

Conclusion:

Given the findings of this study, several recommendations specific to Khyber Pakhtunkhwa(KP) and similar regions can be made to mitigate the impact of air pollution and capitalize on the temporary improvements observed during the COVID-19 lockdown. KP, particularly in urban areas such as Peshawar, would benefit from integrating more stringent emission control policies. Limiting the use of fossil fuels in transportation and industries through incentives for electric vehicles, cleaner fuel alternatives, and industrial emission standards could help sustain the air quality improvements observed during the lockdown. Urban greening initiatives, such as increasing green spaces and tree plantations, can improve urban air quality and act as carbon sinks.These measures should be prioritized in cities like Peshawar and Mardan, where rapid urbanizationhas contributed to increased pollution. Raising awareness among citizens about air pollution and its effects, along with encouraging public transportation, cycling, and other eco-friendly alternatives, could contribute to long-term reductions in air pollution. Governments could use KP'slockdown data as a baseline to show how human behavior changes can lead to significant environmental benefits. Continuous monitoring is crucial for addressing air pollution. Installing more air quality monitoring stations across KP, especially in urban and industrial areas, will provide real-time data for informed decision-making. This is essential to track both the short-termand long-term impacts of policies on air quality. The use of Sentinel-5P satellite data and GoogleEarth Engine should be continued and expanded for ongoing monitoring of air quality. Future studies can integrate more advanced remote sensing technologies to monitor not only air quality but also other environmental indicators like deforestation and urban heat islands, contributing to amore comprehensive environmental strategy. The sharp post-lockdown rebound in SO_2 levels indicates the need for industrial reforms. Cleaner energy sources, such as solar and wind power, should be promoted to reduce dependence on coal and other high-sulfur fuels, especially in KP's growing industrial sectors.

Future research could involve longitudinal studies tracking air quality over several years, especially focusing on the post-COVID era, to evaluate whether temporary lockdown-induced improvements can be replicated through long-term policies. Such studies could identify key factors contributing to both the degradation and improvement of air quality. Further investigations are required to understand how the recovery of different sectors (such as transportation and industry) contributed to the post-lockdown surge in pollutants. Comparing the contributions of various sectors will help target the most impactful interventions. Linking air quality data with health outcomes, such as respiratory diseases, could provide more compelling evidence for stringent air pollution control policies. Studies focusing on the health impacts of pollutant exposure in KP will strengthen the case for cleaner energy and transportation solutions. Similar studies could be conducted in other provinces of Pakistan, comparing regions with varying levels of industrialization and urbanization. This would allow policymakers to better understand the specific drivers of pollution in different contexts. Given the regional context of KP, future research could explore how air quality improvement strategies intersect with broader climate change mitigation and adaptation efforts. This includes examining how cleaner air policies contribute to overall climate resilience.

This study provides critical insights into the impacts of the COVID-19 lockdown on air quality in Khyber Pakhtunkhwa, Pakistan, using Sentinel-5P satellite data. The significant reductions in NO_2, CO, and SO_2 concentrations during the lockdown highlight the direct influence of human activity on air pollution levels. However, the sharp post-lockdown rebound underscores the challenges of maintaining these environmental gains in the absence of long-term structural reforms. The findings emphasize the need for sustainable urban planning, stricter emission control policies, and the promotion of green energy solutions in KP. Furthermore, continuous monitoringusing remote sensing technologies, combined with public awareness campaigns and green initiatives, can play a vital role in sustaining air quality improvements.

In conclusion, while the COVID-19 lockdown provided a unique opportunity to observe the potential for air quality improvements, the rapid resurgence of pollutants post-lockdown demonstrates that temporary measures are not sufficient. Long-term strategies, focused on reducing industrial emissions and promoting cleaner transportation options, will be critical in ensuring a healthier and more sustainable future for KP's urban and rural populations. Future research and policy development must focus on sustaining these environmental benefits through comprehensive, multi-sectoral approaches.

References:

[1] "Impact of lockdown on India's electricity sector | EnergyA." Accessed: Sep. 27, 2024. [Online]. Available: https://www.energy-a.eu/impact-of-ongoing-lockdown-on-indias-electricity-sector-an-overview/

[2] J. Bai et al., "Variations and photochemical transformations of atmospheric constituents in North China," Atmos. Environ., vol. 189, pp. 213–226, Sep. 2018, doi: 10.1016/J.ATMOSENV.2018.07.004.

[3] A. S. Kolawole and A. O. Iyiola, "Environmental Pollution: Threats, Impact on Biodiversity, and Protection Strategies," pp. 377–409, 2023, doi: 10.1007/978-981-19-

6974-4_14.
[4] I. Manisalidis, E. Stavropoulou, A. Stavropoulos, and E. Bezirtzoglou, "Environmental and Health Impacts of Air Pollution: A Review," Front. Public Heal., vol. 8, 2020, doi: 10.3389/fpubh.2020.00014.
[5] F. Ghasempour, A. Sekertekin, and S. H. Kutoglu, "Google Earth Engine based spatio-temporal analysis of air pollutants before and during the first wave COVID-19 outbreak over Turkey via remote sensing," J. Clean. Prod., vol. 319, p. 128599, Oct. 2021, doi: 10.1016/J.JCLEPRO.2021.128599.
[6] S. Muhammad, X. Long, and M. Salman, "COVID-19 pandemic and environmental pollution: A blessing in disguise?," Sci. Total Environ., vol. 728, p. 138820, Aug. 2020, doi: 10.1016/J.SCITOTENV.2020.138820.
[7] S. Gautam, "COVID-19: air pollution remains low as people stay at home," Air Qual. Atmos. Heal., vol. 13, no. 7, pp. 853–857, Jul. 2020, doi: 10.1007/S11869-020-00842-6/FIGURES/5.
[8] M. A. Zambrano-Monserrate, M. A. Ruano, and L. Sanchez-Alcalde, "Indirect effects of COVID-19 on the environment," Sci. Total Environ., vol. 728, p. 138813, Aug. 2020, doi: 10.1016/J.SCITOTENV.2020.138813.
[9] D. Estrada, M. A. R., Kim, N., Park, "The impact of COVID-19 on air pollution: Evidence from global lockdowns," Environ. Pollut., vol. 264, 2020.
[10] S. Ghosh, D. Kumar, and R. Kumari, "Cloud-based large-scale data retrieval, mapping, and analysis for land monitoring applications with Google Earth Engine (GEE)," Environ. Challenges, vol. 9, p. 100605, Dec. 2022, doi: 10.1016/J.ENVC.2022.100605.
[11] M. Singh et al., "Quantifying COVID-19 enforced global changes in atmospheric pollutants using cloud computing based remote sensing," Remote Sens. Appl. Soc. Environ., vol. 22, p. 100489, Apr. 2021, doi: 10.1016/J.RSASE.2021.100489.
[12] Z. Pei, G. Han, X. Ma, H. Su, and W. Gong, "Response of major air pollutants to COVID-19 lockdowns in China," Sci. Total Environ., vol. 743, p. 140879, Nov. 2020, doi: 10.1016/J.SCITOTENV.2020.140879.
[13] "Clear evidence of reduction in urban CO 2 emissions as a result of COVID-19 lockdown across Europe." Accessed: Sep. 27, 2024. [Online]. Available: https://www.researchgate.net/publication/342392861_Clear_evidence_of_reduction_in_urban_CO_2_emissions_as_a_result_of_COVID-19_lockdown_across_Europe
[14] "A breath of fresh air—How air quality has improved during the coronavirus crisis." Accessed: Sep. 27, 2024. [Online]. Available: https://www.reuters.com/graphics/CLIMATE-CHANGE/CORONAVIRUS-POLLUTION/jznvngjyplm/
[15] Y. L. Cheng Fan, Zhengqiang Li, J. Dong, G. de , Ronald van der A, and Leeuw, "Does reduction of emissions imply improved air quality?", [Online]. Available: https://acp.copernicus.org/preprints/acp-2020-1101/acp-2020-1101.pdf
[16] C. Gkatzios, A., Sioutas, M., Theodosi, "Modelling NO_2 concentrations in Thessaloniki, Greece during COVID-19: Impacts of the lockdown," Environ. Monit. Assess., vol. 196, pp. 458–470, 2024.
[17] L. K. Gharibvand, A. A. Jamali, and F. Amiri, "Changes in NO2 and O3 levels due to the pandemic lockdown in the industrial cities of Tehran and Arak, Iran using Sentinel 5P images, Google Earth Engine (GEE) and statistical analysis," Stoch. Environ. Res. Risk Assess., vol. 37, no. 5, pp. 2023–2034, May 2023, doi: 10.1007/S00477-022-02362-4/TABLES/2.
[18] T. Ahmad, S. K. Gupta, S. K. Singh, G. Meraj, P. Kumar, and S. Kanga, "Unveiling Nature's Resilience: Exploring Vegetation Dynamics during the COVID-19 Era in Jharkhand, India, with the Google Earth Engine," Clim. 2023, Vol. 11, Page 187, vol. 11,

no. 9, p. 187, Sep. 2023, doi: 10.3390/CLI11090187.

[19] B. Halder et al., "Machine learning-based country-level annual air pollutants exploration using Sentinel-5P and Google Earth Engine," Sci. Reports 2023 131, vol. 13, no. 1, pp. 1–19, May 2023, doi: 10.1038/s41598-023-34774-9.

[20] S. Wang, H. Chu, C. Gong, P. Wang, F. Wu, and C. Zhao, "The Effects of COVID-19 Lockdown on Air Pollutant Concentrations across China: A Google Earth Engine-Based Analysis," Int. J. Environ. Res. Public Heal. 2022, Vol. 19, Page 17056, vol. 19, no. 24, p. 17056, Dec. 2022, doi: 10.3390/IJERPH192417056.

[21] M. N. Haque, M. S. Sharif, R. R. Rudra, M. M. Mahi, M. J. Uddin, and R. G. A. Ellah, "Analyzing the spatio-temporal directions of air pollutants for the initial wave of Covid-19 epidemic over Bangladesh: Application of satellite imageries and Google Earth Engine," Remote Sens. Appl. Soc. Environ., vol. 28, p. 100862, Nov. 2022, doi: 10.1016/J.RSASE.2022.100862.

[22] M. O. Akbar, H. Malik, F. Hassan, and M. S. S. Khan, "Analysis on Air Pollutants in COVID-19 Lockdown Using Satellite Imagery: A Study on Pakistan," Int. J. Des. Nat. Ecodynamics, vol. 17, no. 1, pp. 47–54, Feb. 2022, doi: 10.18280/IJDNE.170106.

[23] R. Khan, K. R. Kumar, and T. Zhao, "The Impact of Lockdown on Air Quality in Pakistan during the COVID-19 Pandemic Inferred from the Multi-sensor Remote Sensed Data," Aerosol Air Qual. Res., vol. 21, no. 6, p. 200597, Jun. 2021, doi: 10.4209/AAQR.200597.

[24] F. Hassan, M. U. Chaudhry, M. Yasir, M. N. Asghar, and S. A. Sarkodie, "Monitoring the Impact of COVID-19 Lockdown on the Production of Nitrogen Dioxide (NO2) Pollutants Using Satellite Imagery: A Case Study of South Asia," Sustain. 2021, Vol. 13, Page 7184, vol. 13, no. 13, p. 7184, Jun. 2021, doi: 10.3390/SU13137184.

[25] S. Zheng, Q., Ahmad, I., Ali, "Urbanization and its effects on air quality in Pakistan: A satellite-based study of Lahore and Faisalabad," Environ. Sci. Pollut. Res., vol. 31, pp. 1658–1673, 2024.

[26] "Provinces announce easing lockdown even as Pakistan witnesses record rise in coronavirus cases - Pakistan - DAWN.COM." Accessed: Sep. 27, 2024. [Online]. Available: https://www.dawn.com/news/1555575

[27] "The News. (2020, March 23). Pakistan imposes nationwide lockdown to contain COVID-19. The News International.", [Online]. Available: https://www.thenews.com.pk/latest/635364-pakistan-imposes-nationwide-lockdown-to-contain-covid-19

[28] Al Jazeera., "Pakistan lifts lockdown as COVID-19 cases drop," Al Jazeera News, [Online]. Available: https://www.aljazeera.com/news/2020/8/7/pakistan-lifts-lockdown-as-covid-19-cases-drop

[29] H. Gharibvand, L., Ghahremanlou, R., Javanmard, "Assessing air pollution during COVID-19 using Sentinel-5P data in Iran: A Google Earth Engine approach," Atmos. Environ., vol. 250, pp. 118–129, 2023.