Analyzing Seasonal Variations in Air Quality with Google Earth Engine: A Case Study of Chattogram, Bangladesh

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ANALYZING SEASONAL VARIATIONS IN AIR QUALITY WITH GOOGLE EARTH ENGINE: A CASE STUDY OF CHATTOGRAM, BANGLADESH

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Keywords:

- Air Quality
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- $PM_{2.5}$
- PM_{10}
- Remote Sensing

Abstract: Air pollution is a serious environmental challenge in Bangladesh, significantly affecting public health and the ecosystem. This study considers analyzing the seasonal fluctuation of air quality in Chattogram by analyzing 13 significant areas near the industrial zone by using Google Earth Engine (GEE) to explore the SENTINEL-5P satellite data for key pollutants, including nitrogen dioxide (NO2), sulfur dioxide (SO_2), and carbon monoxide (CO), and QGIS for mapping purposes. The datasets were assessed through four different seasons: winter (December - February), pre-monsoon (March - June), monsoon (July - September), and post-monsoon (October - November). It is found that significant trends over the seasons—where the winter shows the maximum level of pollutant concentrations, i.e., NO_2 shows 0.000200 mol/m2 in Patiya and 0.000059 mol/m2 at Bayezid Bostami in the monsoon, and SO_2 shows 0.000394526 mol/m2 in Chittagong Port and 0.0000152 mol/m2 in the monsoon period in Bakalia. The variation intensely indicates the changes in concentrations of pollutants over the season and has a strong negative correlation between precipitation, temperature, humidity, and wind velocity. The monsoon season enhances air quality, effectively dispersing rainfall and significantly lowering pollutant levels. Furthermore, the analysis highlights the hotspots or sources of the pollutant all over the year. This study enhances policymakers' understanding of urban air quality by providing actionable strategies to reduce air pollution.

1. Introduction

Human actions, including the combustion of fossil fuels, industrial activities, and changes in Land Use and Land Cover (LULC), result in increased pollutants such as NOx, SO_2, CO, HCHO, and CH_4(Seinfeld & Pandis, 2016). These emissions are significant in climate change, the greenhouse effect, and global warming (IPCC, 2021). Air pollution contains harmful substances such as $PM_{2.5}$, PM_{10}, NO, NO_2, SO_2, CO, and O_3, leading to serious consequences. These cause global warming, higher temperatures, acid rain, and ozone layer depletion. According to WHO (World Health Organization), air pollution causes over 6.7 million premature deaths annually. In 2019, 99% of the world's population lived in places where WHO guidelines were not met. This issue is so critical that it is linked to three Sustainable Development Goals (SDGs): good health and well-being (Goal 3), affordable and clean energy (Goal 7), and sustainable cities and communities (Goal 11). Rapid urbanization and industrial growth have worsened air pollution, particularly in developing regions. Over the past century, Earth's average surface temperature has risen by 0.74°C and is projected to increase by 1.5–2°C by 2100, a 0.1°C decadal rise (IPCC, 2021). It drives extreme droughts, floods, storms, and wobbles ecosystems and human health as this warming intensifies the global water cycle. There are indeed seasonal variations in weather, such as heavy monsoon rains and dry winters, in Chattogram, which directly impact the air quality patterns.

Google Earth Engine is a cloud-based, open-source geospatial analysis platform for analyzing satellite data (Gorelick et al., 2017). It is utilized to study air quality patterns over time in a significant industrial hub in Chattogram. From SENTINEL-5P, major air pollutants such as SO_2, NO_2, and CO were analyzed(Veefkind et al., 2012). Additionally, meteorological parameters, including temperature, wind speed, and humidity, are integrated from FLDAS (Famine Early Warning Systems Network Land Data Assimilation System) and ERA5 (the European Centre for Medium-Range Weather Forecasts Reanalysis) to assess their influence on air pollution variability(McNally et al., 2017). These datasets are widely used for analyzing air pollution trends. QGIS is another open-source GIS software widely used for mapping and analysis purposes. We've implemented QGIS for analysis, zonal statistics, and map preparation.
Chattogram is Bangladesh's second-largest city, serving as an industrial center and the nation's port facility, which maintains critical economic value. The contaminants from industries and motor vehicles coupled with port operations

have produced unacceptable air quality standards throughout Chattogram, thus creating noteworthy health problems for its citizens. The rapid growth of industrialization, inadequate air quality regulations, and insufficient public health infrastructure exacerbate the pollution problem. The region faces an extensive problem affecting public health and sustainable regional development. Knowing air quality trends and their pollution components enables the creation of effective measures to safeguard public health and environmental protection.

2. Study Area

Chattogram, located in the southeastern region of Bangladesh, spans approximately between 21°54′N to 22°59′N latitude and 91°17′E to 92°13′E longitude near the Bay of Bengal, bordered by the Chittagong Hill Tracts to the east and the coastline to the west. It has the largest seaport in the country and is 67th in the world, handling more than 90% of the nation's trade with the most significant economic zone named CEPZ(Islam et al., 2021). The research focused on 13 thanas that were strategically selected based on their proximity to industrial and economic zones and surrounding residential areas. This research utilized data on NO_2, SO_2, and CO concentration collected from the Sentinel-5P satellite, covering the period from 1st December 2022 to 30th November 2023.

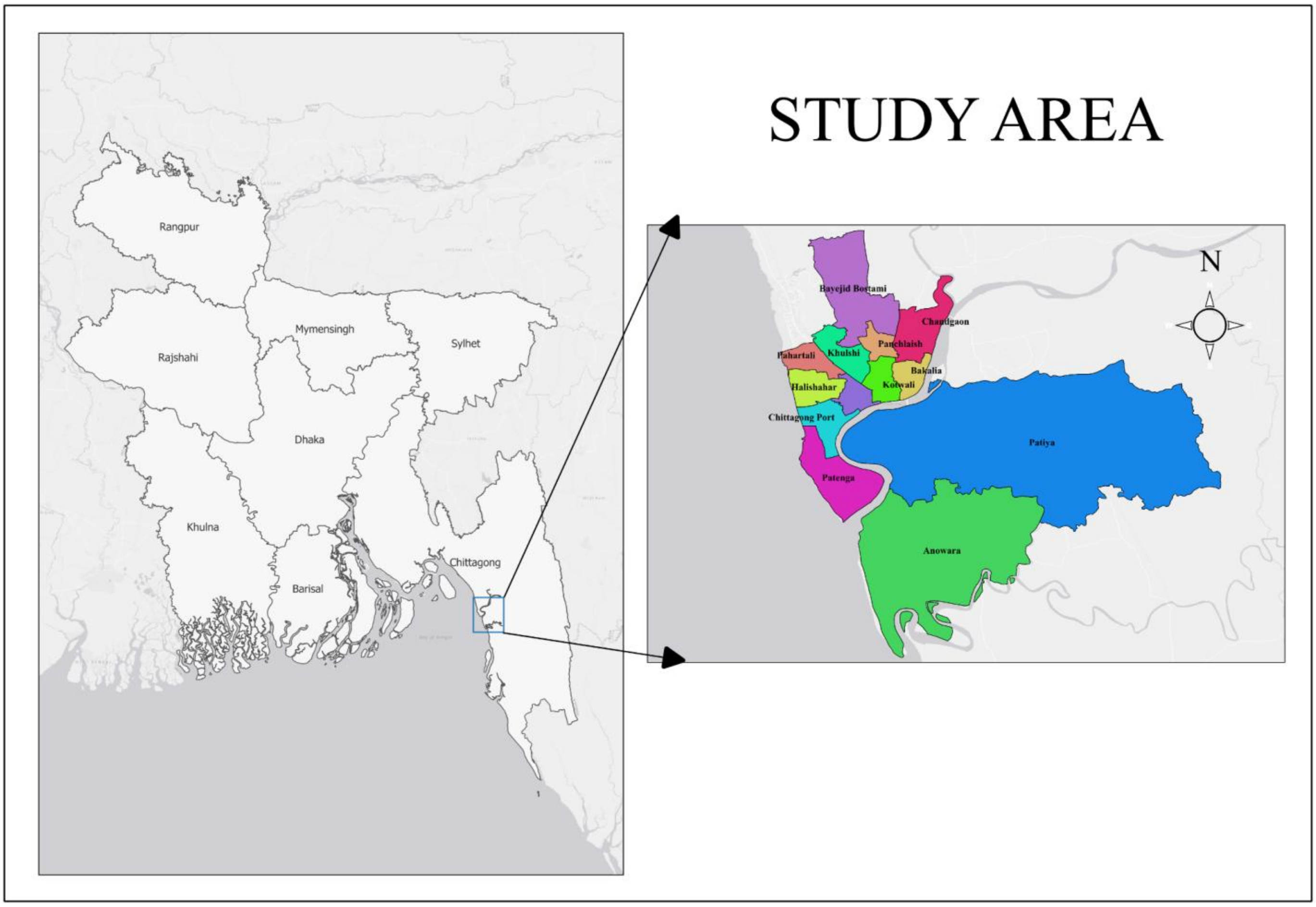


Fig. 2.a Location of significant areas of Chattogram City (Study Area)

3. Materials and Methods

The datasets utilized for mapping and analyzing the concentrations of the core pollutants across 13 major areas in Chattogram's industrial zone. ERA5 and FLDAS include meteorological factors such as precipitation, temperature, wind speed, and humidity throughout the seasons.

3.1 Dataset Collection

Sentinel 5P

The Tropospheric Monitoring Instrument (TROPOMI) instruments, which are multispectral sensors, are used in the Sentinel 5P mission to measure nitrogen oxide, carbon monoxide, methane, sulfur dioxide, formaldehyde, and ozone using various reflectance wavelengths. Sentinel-5P has up to 5.5 km x 3.5 km of spatial resolution and delivers global coverage of pollutants every 48 hours.

ERA5

ERA5, the successor of ERA-Interim, is a fifth-generation European Centre for Medium-Range Weather Forecasts (ECMWF) for the global climate and weather monitoring mission, with global coverage for the past eight decades (Hersbach et al., 2020). ERA5 provides aggregated values of 2m air temperature, 2m dew point temperature, total precipitation, surface pressure, and 10m u & v wind speed components with a spatial resolution of 27.83 km.

FLDAS

The FLDAS dataset assessed food security in developing countries. It includes various climate parameters such as humidity and wind speed, featuring a spatial resolution of 11.1 km x 11.1 km, global coverage, and a temporal resolution of 1 month(McNally et al., 2017).

Open Street Map

OpenStreetMap (OSM) is an open-source mapping project that provides editable geographic data on roads, buildings, and industrial sites. Overpass Turbo is a tool for querying OSM data, such as the number of factories in an area. Using the Overpass Turbo API helps identify potential pollutant hotspots, as industrial regions are often associated with higher pollution levels.

3.2 Methodology

Chattogram is Bangladesh's second-largest city, with approximately 32 million residents, of whom about 5 million live in urban areas. It is a crucial industrial powerhouse that fosters growth in export zones and operates numerous thriving factories. The data used for analysis was obtained from Sentinel 5P onboarding Tropospheric Monitoring Instrument (TROPOMI) to collect various spatial and temporal parameters. This information is crucial for mapping and evaluating the key air quality pollutants that harm the environment and humans. Google Earth Engine (GEE) is an open-source, cloud-based platform for processing spatial and temporal datasets within designated regions of interest. The code editor integrated JavaScript to access, manipulate, and analyze datasets over the study area in four seasons using Sentinel-5P. Here is the flowchart for how the datasets were collected and analyzed.

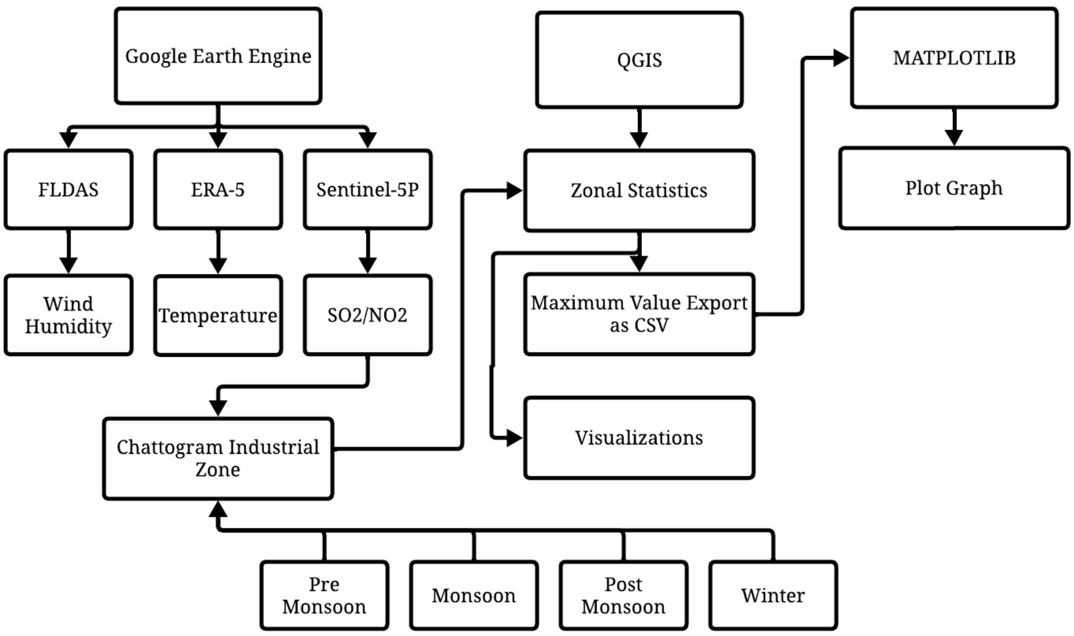


Fig. 3.2.a Flowchart of research process.

Sentinel-5P provides the column number density for pollutants such as SO_2, NO_2, and CO, measured in units of mol/m². This value represents the total vertical column of each pollutant, which is calculated as the ratio of the slant column density to the total air mass factor. The data collection period is classified into four seasons: winter (December 2022 - February 2023), pre-monsoon (March 2023 - June 2023), monsoon (July 2023- September 2023), post-monsoon (October 2023- November 2023) for 13 influential areas inside the Chattogram city respectively Anowara, Bakalia, Bayezid Bostami, Chandgaon, Chittagong Port, Double Mooring, Halishahar, Khulshi, Kotwali, Pahartali, Panchlaish, Patenga, and Patiya.

In GEE, each pollutant's concentration was exported using JavaScript codes for uploaded shapefiles for specific temporal periods. The output file in GEE is generated in TIFF format. The raster data was then imported into QGIS for map preparation. Zonal statistics were performed for each season and pollutants to extract the maximum concentration (mol/m2) of each pollutant for the specified areas(Bivand et al., 2013). The data was then exported in CSV format for further analysis. For the meteorological factors, the maximum temperature(K) and precipitation(mm) from ERA5 and average wind speed (m/s) and humidity (mass fraction) from FLDAS were exported directly into CSV format for each season and region of interest.

3.3 Statistical Analysis

This study uses Pearson Correlation analysis to understand better the relationship between pollutants and meteorological factors like precipitation, humidity, wind speed, and temperature. This method analyzes the strength and direction of two parameters with values ranging from -1 to 1. Positive values indicate that the two variables increase together (proportional relationship), while negative values suggest that one variable decreases as the other increases (inverse relationship).

The Pearson correlation coefficient (*r*) is calculated using the following formula:

$$r = \frac{\sum_{i=1}^{n}(x_i - \bar{x})(x_i - \overline{y})}{\sqrt{\sum_{i=1}^{n}(x_i - \bar{x})^2 . \sum_{i=1}^{n}(y_i - \overline{y})^2}}$$

Where:

- x_i and y_i are the data points for the two variables being compared
- $\overline{x}$ and $\overline{y}$ are the mean values of the variables x and y
- n is the total number of data points
-

The correlation value is categorized to interpret the relationship between two parameters, shown below in Table 1.

Table 1: Correlation Strength Classification

Value Range	Strength of Correlation
0.2 to 0.5	Weak
0.5 to 0.8	Moderate
0.5 to 0.8	High

4. Results

The following results are shown from seasonal data of NO_2, SO_2, and CO pollutants collected and analyzed using GEE, QGIS, and Statistical analysis.

4.1 NO_2

Nitrogen dioxide (NO_2) concentrations(mol/m^2) are highest in industrial areas, specifically Anowara, Patenga, and Patiya, as shown in Fig 4.1.a. The peak concentration of NO_2 occurred during the winter months, recorded at 0.000202 mol/m^2. NO_2 levels were consistently lowered during the pre-monsoon and monsoon seasons, and their lowest average was 0.000069 mol/m^2. A negative correlation of NO_2 concentration level was also observed for several meteorological factors, including wind speed, precipitation, humidity, and temperature(Begum et al., 2011).

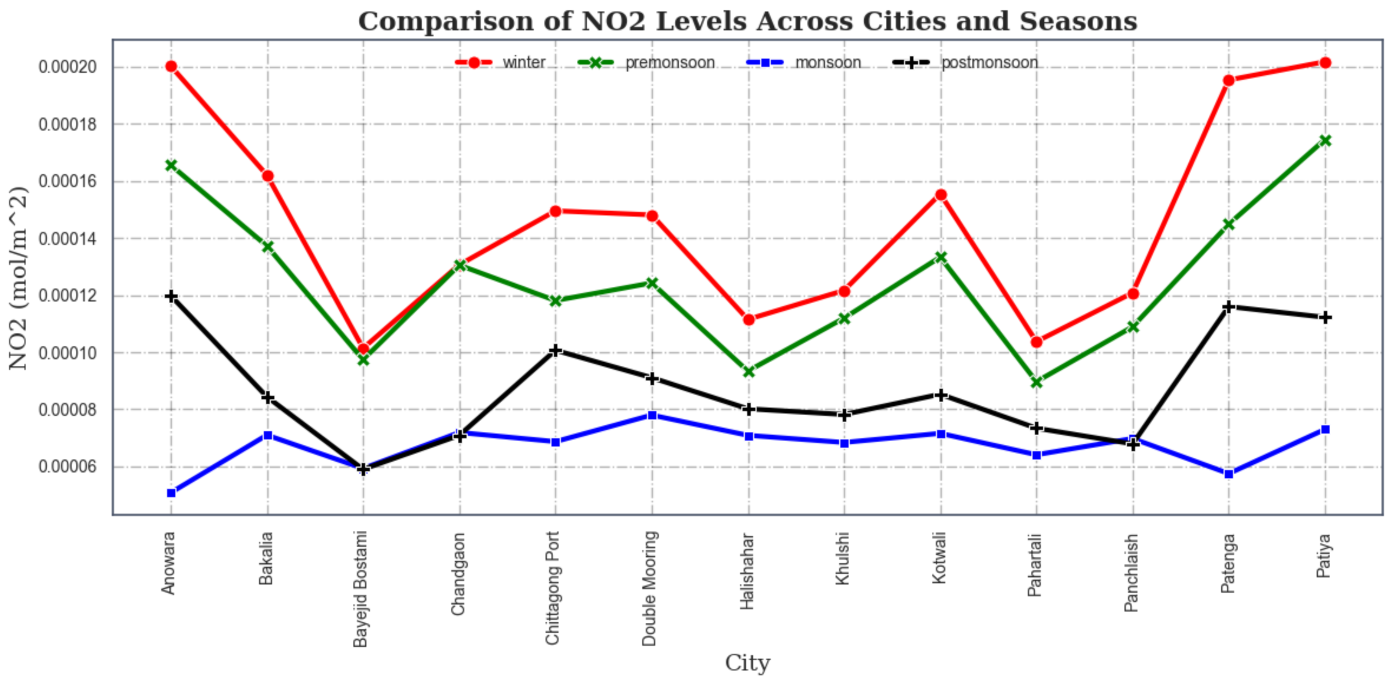


Fig 4.1.a Seasonal Variations in NO_2 Levels Across Cities

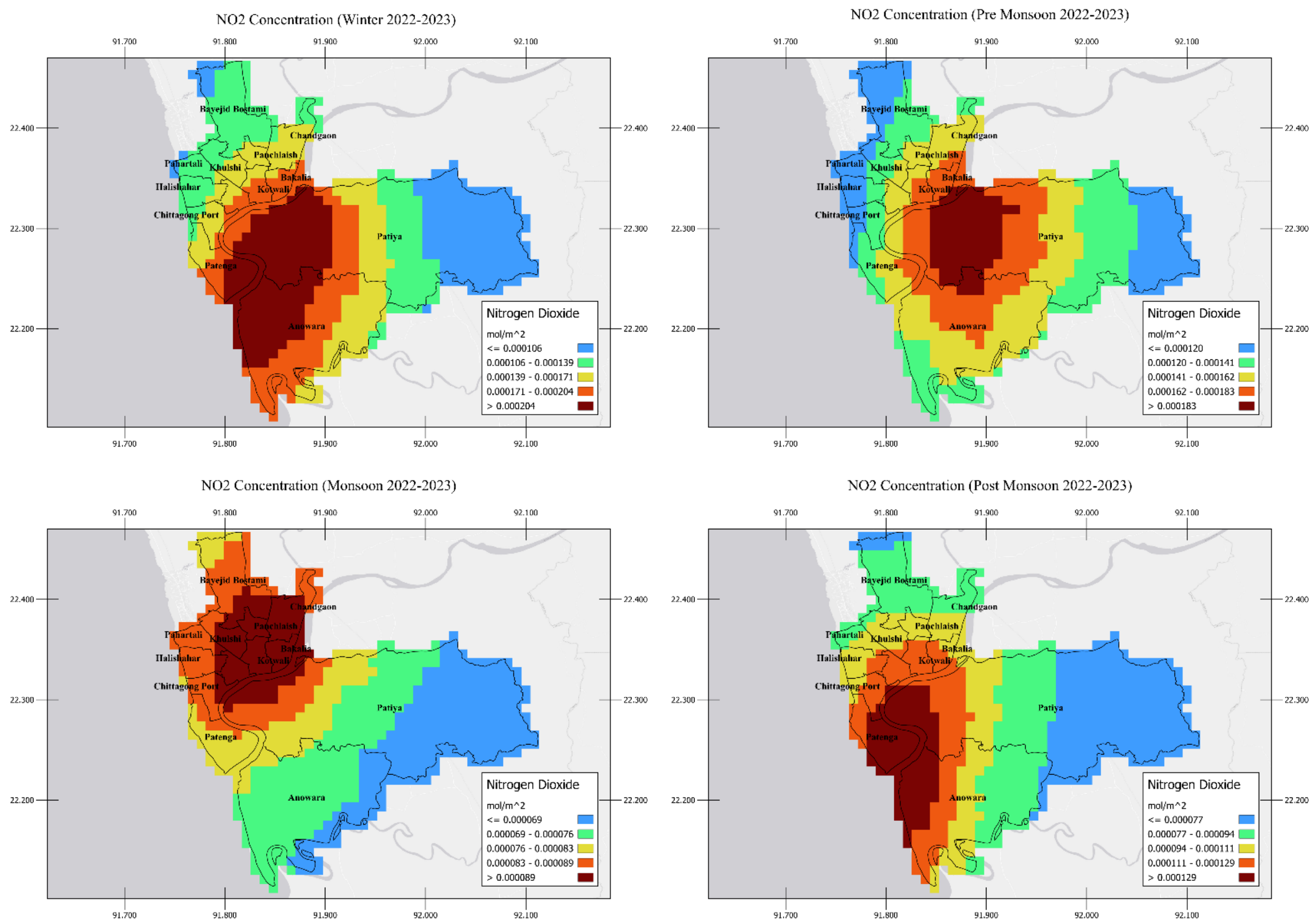


Fig 4.1.b Spatial Distribution of NO_2 Concentration During Winter 2022–Post Monsoon 2023

Figure 4.1.b illustrates that the hotspot area is significantly larger in winter than in the other three seasons, and its intensity is notably high. In contrast, during the pre-monsoon, monsoon, and post-monsoon periods, the hotspot is smaller and shifts location due to the effects of the wind and precipitation.

4.2 SO_2

As shown in Figures 2a, 2b, 2c, and 2d, the concentration of Sulfur Dioxide (SO_2) in mol/m² was maximum in the areas of such industries: Anowara, Patiya, Double Mooring, and Chittagong Port. During the winter, the peak of SO_2 concentrations was 0.0004 mol/m². At the same time, SO_2 levels dropped quickly during the monsoon season by 90% compared to winter. Pearson analysis indicates a negative correlation between SO_2 concentrations and meteorological factors such as wind speed, precipitation, humidity, and temperature.

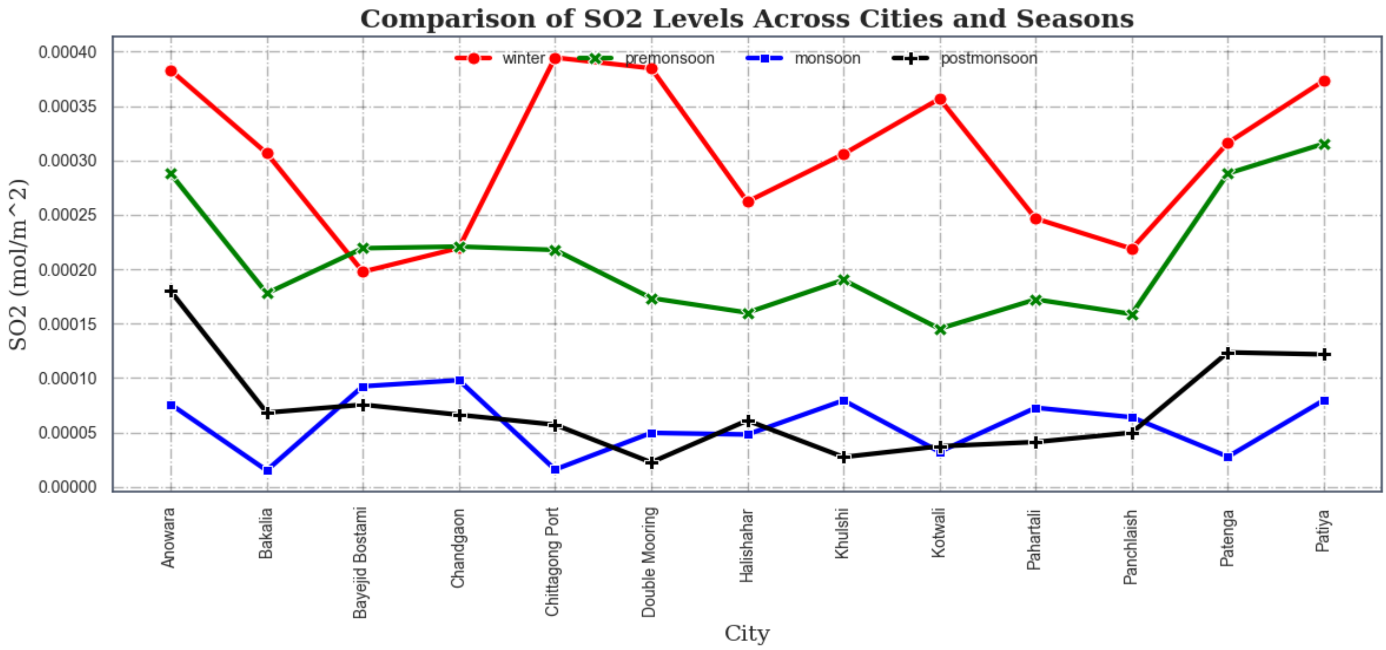


Fig 4.2.a Seasonal Variations in SO_2 Levels Across Cities

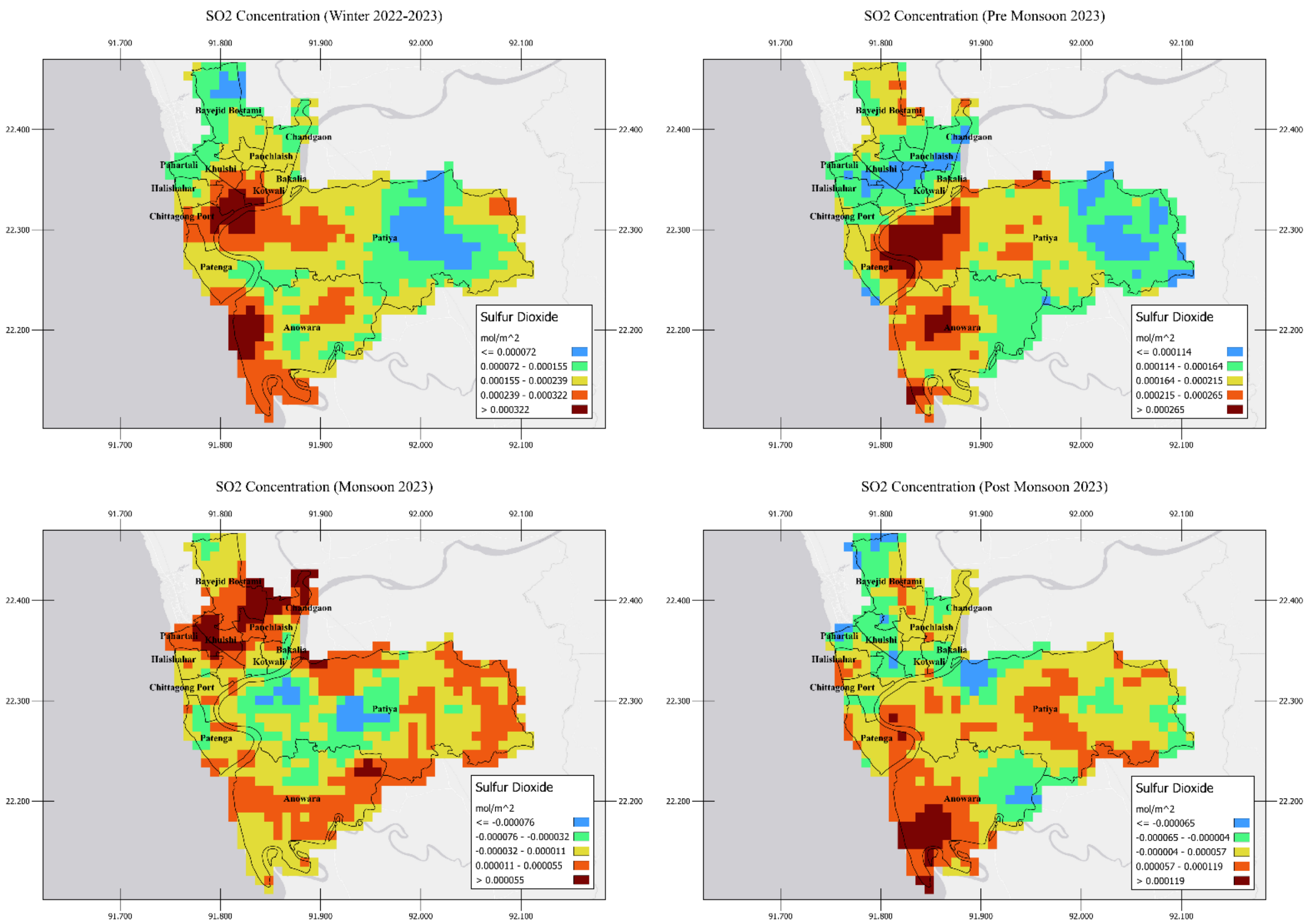


Fig 4.2.b Spatial Distribution of SO_2 Concentration During Winter 2022–Post Monsoon 2023

4.3 CO

Due to vehicular emissions and industrial activities, carbon monoxide is primarily found high during the winter, pre-monsoon, and post-monsoon. As shown in Fig 4.3.b, areas with high population density and extensive road networks exhibit greater concentrations of carbon monoxide during these three specific seasons. On the other hand, during the monsoon, the concentration level drops by 20% on average, and the affected area is also reduced by the wind effect and rainfall.

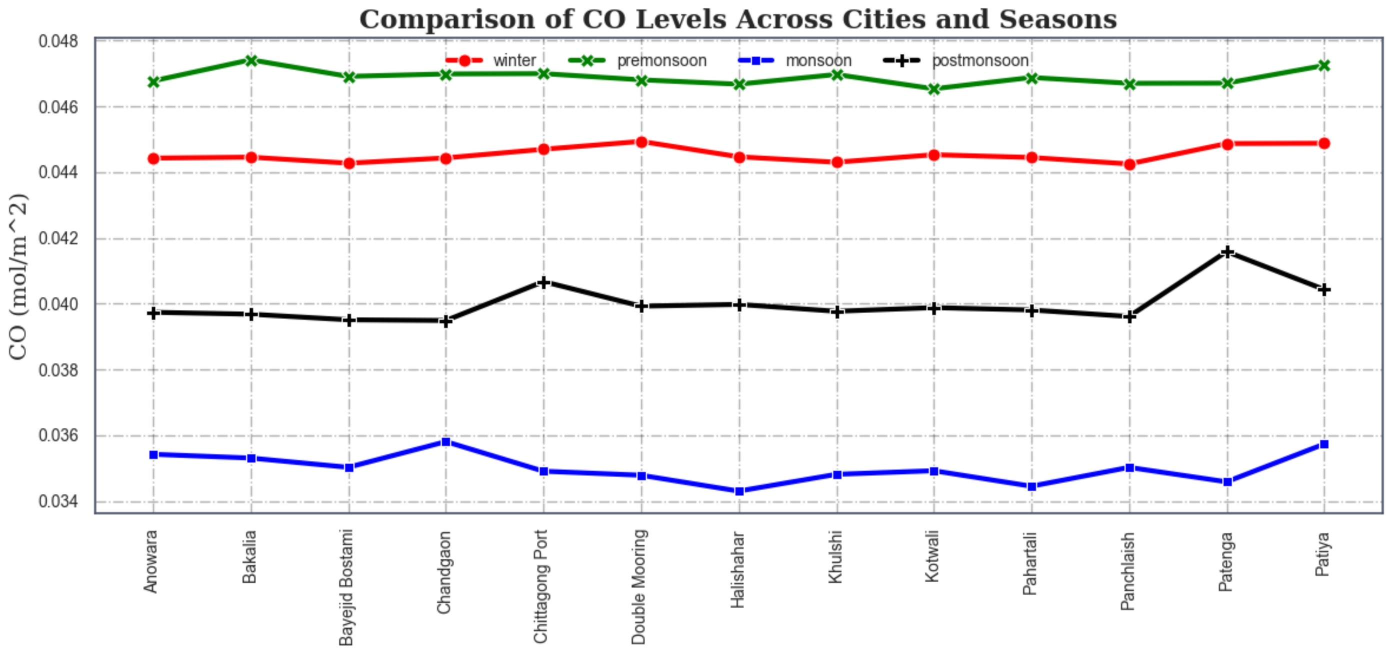
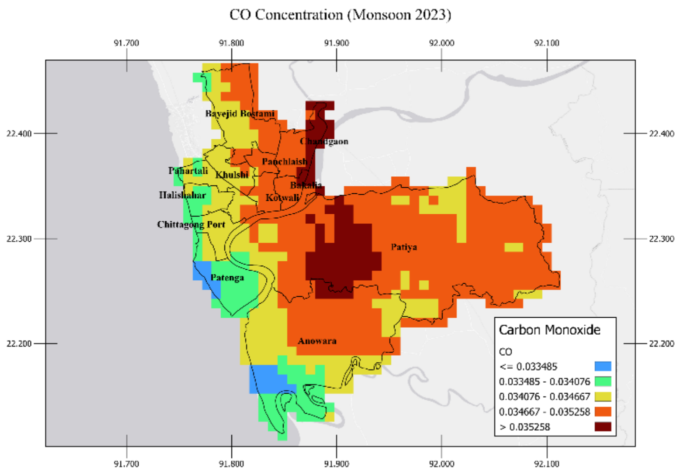
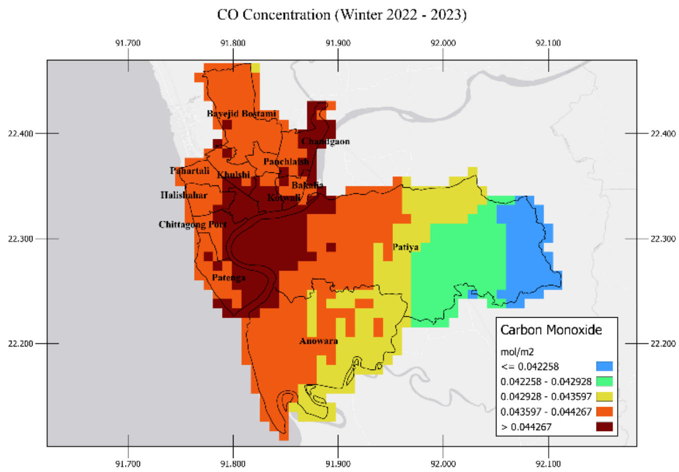


Fig 4.3.a Seasonal Variations in SO_2 Levels Across Cities





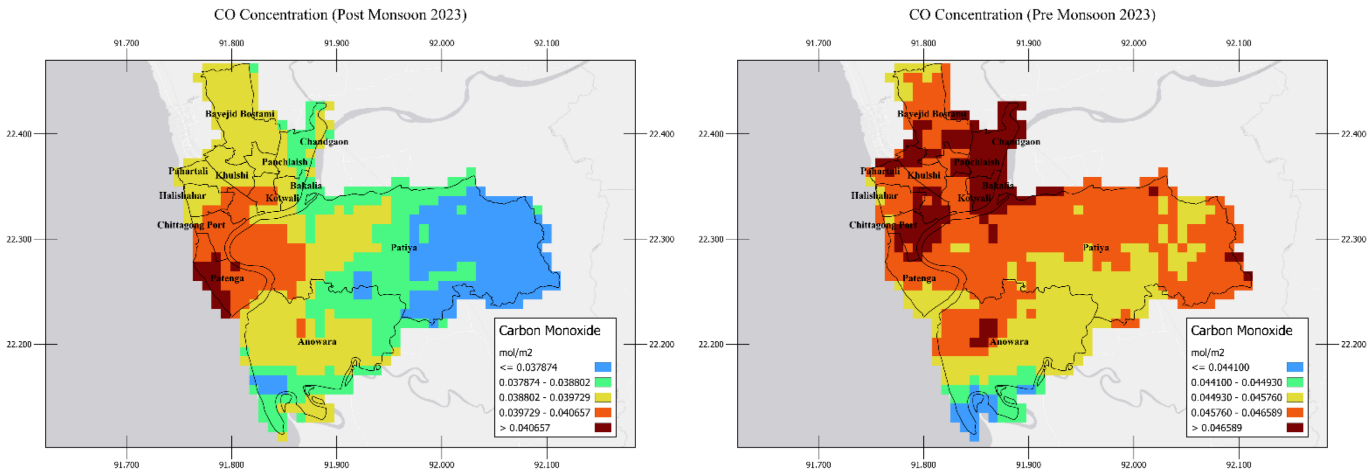


Fig 4.3.b Spatial Distribution of NO_2 Concentration During Winter 2022–Post Monsoon 2023

4.3 Pearson Correlation Analysis

We ran a Pearson correlation analysis to understand how environmental factors affect the concentrations of our gases (NO_2 and SO_2)(Carslaw & Ropkins, 2012). This statistical tool helped us determine the strength and direction of the relationships between each gas and key weather conditions: wind speed, precipitation, humidity, and temperature. We summarized the correlation coefficients in the table below:

Table 2: Pearson correlation coefficient of pollutants with meteorological factors.

Pollutant	Precipitation	Wind	Temperature	Humidity
NO_2	-0.83	-0.70	-0.69	-0.94
SO_2	-0.80	-0.65	-0.73	-0.94
CO	-0.84	-0.78	-0.31	-0.76

This analysis indicates that all meteorological factors negatively correlate with each type of pollutant. Key elements such as wind, precipitation, temperature, and humidity vary with the changing seasons. For instance, wind velocity and precipitation tend to increase during the monsoon season compared to winter months, reducing pollutants, including various other contaminants.

5. Discussion

5.1 NO_2

The dominant source of nitrogen dioxide (NO_2) production is burning fossil fuels during transportation operations, industrial activities, and power plants. NO_2 functions as an essential contaminant, leading to polluted air environments that result in respiratory health issues and making acid rain and ozone formation near the ground possible(Faustini et al., 2014). The analysis shows that NO_2 peaks in winter because industrial facilities and vehicles increase emissions(Monks et al., 2015). The combination of low wind speed and atmospheric stability during wintertime creates surface conditions that trap pollutants, thus causing elevated NO_2 air concentrations. In some areas, the monsoon season leads to NO_2 reduction levels up to 95%. Open winds and heavy rainfall help reduce NO_2 levels in the atmosphere by dispersing pollutants and washing out the substance through precipitation. The study confirms the wind and rainfall impact on NO_2 levels by showing their negative correlation with meteorological factors since these natural processes reduce pollution levels during the monsoon season.

5.2 SO_2

Industrial companies utilize sulfur-containing fossil fuels for combustion, primarily resulting in sulfur dioxide (SO_2) emissions(Fowler et al., 2020). The resulting air pollution contributes to the formation of acid rain, which causes soil acidification and contamination of coastal waters. This ultimately disrupts ecosystems and degrades water quality. The analysis shows SO_2 pollution keeps high concentration levels in Anowara, Patiya, Double Mooring, and Chittagong Port throughout the year. The industrial areas supporting many fossil fuel-based plants and industries consistently record high SO_2 levels, surpassing permitted limits owing to their industrial emission sources. During winter, SO_2 levels reach their maximum wind speeds remain slow, and atmospheric conditions stay unchanged, thus preventing pollutants from escaping ground-level contamination. The absence of precipitation permits SO_2 pollution levels to be sustained at high concentrations since it remains in the atmosphere for extended periods. But in monsoons, SO_2 levels decrease to almost one-tenth of the winter seasons. The combination of intense rainfall and windy conditions results in a significant devaluation of SO_2.

5.3 CO

The incomplete combustion of fossil fuels significantly contributes to carbon monoxide (CO) emissions, especially during winter, pre-monsoon, and post-monsoon seasons(Seinfeld & Pandis, 2016). During these times, light winds and heavy traffic lead to elevated CO levels, particularly in urban areas, where concentrations often exceed safety limits(Rana et al., 2022). In winter, stagnant air and limited ventilation trap pollutants near the ground. At the same time, the lack of rain accumulates CO. Conversely, the onset of the monsoon brings increased rainfall and stronger winds, effectively reducing CO pollution by dispersing harmful emissions and providing relief to urban environments.

6. Conclusion

The study considers the effects of NO_2, SO_2, and CO in the industrial areas of Chattogram in Bangladesh. Satellite data from the Sentinel-5P mission's TROPOMI instrument are used in the study to map and analyze these pollutants traced from different seasons, such as winter, pre-monsoon, monsoon, and post-monsoon. Pollutants found through the findings vary in the various areas of Chattogram within these seasons. For example, nitrogen dioxide concentrations (NO_2) vary extensively by region and are higher in industrial and urban areas like Anowara, Patiya, and Chattogram Port. Furthermore, the sulfur dioxide (SO_2) concentration also varies, which generally increases with higher industrial activity. Results indicate that carbon monoxide CO tends to accumulate in Chattogram City as an urbanized zone, especially in the city's central region, due to the transportation and industrial effects. In winter, particle matter concentrations are higher due to low wind speeds and less air movement.

The research also comprehensively reviews seasonal variations and spatial patterns of these pollutants in Chattogram. During the winter, CO varies from 0.042 to 0.044 mol/m², the concentration of NO_2 up to 0.0002 mol/m², and SO_2 0.00032 mol/m². However, pollutant concentration decreased by 80–90 % from case to case for each pollutant, mainly due to heavy rainfall and strong winds that removed contaminants from the atmosphere. These findings have important implications for public health and environmental management. They deliver essential information on the shape of regional, tailored strategies for combatting and reducing air pollution.

The pollutant concentrations vary greatly, which allows the identification of the areas that are sensitive to air quality problems, assisting in the intervention actions. Sentinel-5P data are effectively used for remote sensing of the pollution distribution through satellite and air pollution monitoring. As informed by this study, the levels of pollutants in Chattogram are valuable clues to formulating environmental policy, public health interventions, and urban planning for Chattogram's regional development.

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