Spatial Trend Analysis of Atmospheric Pollutants in Chattogram District of Bangladesh using Sentinel-5 TROPOMI Images

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ABSTRACT: Air pollution is a major concern worldwide especially in developing countries like Bangladesh due to rapid industrial growth and unplanned urbanization. Despite being the country's commercial hub, Chattogram has not been sufficiently studied in terms of air pollution. This research aims to address this gap by determining the trend of air pollutants and identifying their sources in Chattogram. Using satellite-based remote sensing data from Sentinel-5 TROPOMI, spatial and seasonal changes of six air pollutants: Nitrogen dioxide, Sulfur dioxide, Carbon Monoxide, Formaldehyde, Methane, and Aerosol have been observed for the years 2019 to 2023. Moreover, qualitative surveys with local residents and industrial workers were done to compare the consistency of the results and the perceived impact of relevant stakeholders. The trends show overall increasing concentrations for all the pollutants over the years notably near the industrial areas and seaport of Chattogram with a decline during the COVID-19 pandemic suggestive of reduced industrial activities. The concentrations in the dry seasons were higher than in the wet seasons and the qualitative survey revealed that the industrial workers perceived air pollution as more severe than the residents. The growing trend of air pollutants and the community perceptions obtained from this research highlight the need for continuous monitoring of the air quality, demarking the high concentration pollution zone, targeting measures for reducing emission at-source and sustainable agricultural practices. Recognizing the threat, and coordinating public and private efforts are crucial to mitigating air pollution emissions and ensuring a better future for the upcoming generations.

Keywords: Air Pollution; Trend Analysis; Sentinel-5P TROPOMI; Spatial Distribution; Seasonal Variation

INTRODUCTION

Air pollution is a major concern across the globe. Pollutants and dust particles in the air are considered responsible for almost 7 million premature deaths all over the world mostly due to lung cancer, stroke, and respiratory inflammation. (WHO, 2022). Given attention to this critical situation, developed nations have reduced their dependence on fossil fuels and have shifted to sustainable energy sources. In contrast, the developing nations are being affected by air pollution continuously as most of them are dealing with unplanned urbanization. (Thangavel et al., 2022). Likewise, Bangladesh, a developing country with rapid industrialization and unplanned urbanization is confronting the air pollution problem (Khandker et al., 2022; Rahman & Al-Muyeed, 2005). The construction and industrial activities are causing the release of significant amounts of air pollutants and dust particles, making the country's atmosphere one of the worst in the world (Rana et al., 2021). Almost 1,23,000 deaths were linked with air pollution in 2017 which increased to 1,73,500 in 2019 in Bangladesh. Three major sources of air pollution are believed to be brick kilns, motor vehicles, and power plants. Brick kilns and coal-dependent power plants produce significant amounts of Sulfur dioxide (SO_2), Nitrogen dioxide (NO_2), and other pollutants that are degrading the quality of our air (Khandker et al., 2022). Apart from these three sources, other sources like the industries of production and processing (textile, pharmaceutical, footwear, oil refinery etc.) add to the air pollutants in the atmosphere.

In recent years, the heavily industrialized and unplanned urbanized cities of Bangladesh have frequently surpassed hazardous levels experiencing significant deterioration in their Air Quality Index (AQI). Dhaka and Chattogram were at the forefront of this list (Hossen et al. 2018). Dhaka, the capital of

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Bangladesh could capture the focus of the scientific community, resulting in multiple investigations (Aktar & Shimada, 2014; Begum et al., 2011; Habib & Mohammed, 2002; Khuda, 2020). Chattogram, though being the commercial capital of Bangladesh lacks sufficient attention from the researchers and policy makers regarding the air pollution context. An inadequate number of studies have been carried out for Chattogram. Due to the growing industrial activities and the presence of a significant number of unregulated brick chimneys, it is essential to observe the trend of atmospheric pollutants in Chattogram. Identifying the high zone of concentration and the possible sources of excessive emission of pollutants has become essential. Hence, this research aims to inspect the air pollution issue in Chattogram.

Various techniques for assessing air quality have been developed to effectively monitor and analyze pollution levels. Each method offers unique advantages and limitations, influencing their applicability in different contexts (Marć et al., 2015). Long-term air quality monitoring over extensive areas using ground-based monitoring stations faces several challenges, including an inadequate number of monitoring stations, high maintenance costs, and limited data collection capabilities. Additionally, the uneven distribution of these stations significantly impedes the ability to accurately map variations in air quality across large regions. In contrast, remote sensing-based air quality monitoring overcomes these limitations. It utilizes satellite technology to assess and track atmospheric pollutants over large geographic areas, providing valuable data that complements ground-based measurements. This approach enables continuous observation of air quality patterns and trends, facilitating better understanding and management of pollution sources and their impacts on human health and the environment. The satellite images produce average concentration for each pixel and trend analysis for a bigger scale becomes cheaper and easier (Engel-Cox et al., 2013; Engel-Cox et al., 2004; Lahoz et al., 2012; Maurya et al., 2022; Morozova et al., 2022; Singh et al., 2021). Therefore, our study has opted for sentinel 5P TROPOMI (Tropospheric Monitoring Instrument), which is a multispectral sensor that has the ability to record reflectance from different air particles to categorize them into different air pollutants (Maurya et al., 2022; Morozova et al., 2022; Rana et al., 2021). Sentinel 5P TROPOMI data were used to analyze the change in concentration of six different air pollutants named Nitrogen dioxide (NO_2), Sulfur dioxide (SO_2), Methane (CH_4), Carbon monoxide (CO), Formaldehyde (HCHO), and Absorbing Aerosol Index (AAI).

NO_2 mostly occurs from anthropogenic activities including fossil fuel combustion in vehicles, refining of petroleum, and food production. SO_2 a significant contributor to acid rain is mainly from coal-fired and gas-dependent plants and electric utilities in addition to industrial processes such as cement manufacturing and petroleum refining. Coal burning contributes notably to SO_2 emissions by releasing Sulfur into the atmosphere (Adesina et al., 2021; McDuffie et al., 2020). CO is primarily produced through the incomplete combustion of fossil fuels and coal, with significant emissions typically linked to industrial activities and transportation. South Asia, including Bangladesh, is recognized as a global hotspot for CO production (Cakmak et al., 2023). HCHO is a pervasive pollutant from both natural and anthropogenic processes originating from sources such as forest fires, bushfires, decomposition of organic materials, and industrial and vehicular emissions in addition (Li et al., 2024). CH_4 a potent greenhouse gas with a much stronger heat-trapping ability than CO_2, is emitted from agricultural activities, fossil fuel extraction, and wetlands, contributing to global warming and ozone formation. Finally, AAI is a measure of atmospheric absorbing aerosols including black carbon, mineral dust, and soil dust. AAI is influenced by human activities, wind cover, and cloud cover (Kooreman et al., 2020).

Our research aimed to identify crucial hotspots for various air pollutants and suggested potential sources contributing to the air pollution problem. Additionally, it has demonstrated the changes in air pollutant concentrations in wet and dry seasons. While the satellite imagery-based results could not be directly compared with primary ground-based data, ground-based secondary data was collected from the Department of Environment (DoE) to compare the findings. Additionally, qualitative surveys were conducted among local people to analyze the consistency of their perception with the implications from the satellite-based data and also for a better understanding of the pollution landscape. Respondents provided insights into their experiences of pollution over the past five years, revealing significant seasonal and spatial trends. This study emphasizes the importance of both seasonal and spatial variations in air quality, particularly given the coexistence of residential areas and industrial activities in Chattogram. Understanding these spatial variations is crucial for making informed policy decisions for pollution control. Moreover, the findings may help in zonation of the more polluted area and adopting effective public and private interventions aimed at mitigating air pollution from the potential sources in Chattogram.

STUDY AREA

We have selected Chattogram district as our study area (Fig. 1). Chattogram district, one of Bangladesh's trade-centered districts, is located between 21°54' N and 22°59' N, and between 91°17' N and 92°13' N (Banglapedia, 2024). The district is surrounded by Khagrachhari and Rangamati districts of Bangladesh, Tripura state of the neighboring country India to its north, and Cox's Bazar to its south. It is surrounded from the east by three of the Chattogram hill tract districts: Khagrachhari, Rangamati, and Bandarban. To the west, it is bordered by Noakhali district and the Bay of Bengal. The district has a total area of 5282.92 km^2, and its population is 9,169,465 (Ministry of Planning, 2023). Our study area is uniquely characterized by its topography; a blend of hills, valleys, and floodplains (Chowdhury & Haque, 2020). Annual precipitation of the district ranges between 2735 mm to 3194 mm (Bangladesh Meteorological Department, 2024). Since the region has the main seaport of Bangladesh, our study area serves as the significant commercial capital of the country. Many industries, including production and processing facilities, have established themselves to bolster the district's commercial activities. Apart from industrialization, several development projects such as road, and bridge construction supporting rapid urbanization are also prevalent here. These industries and development activities may significantly contribute to the emission of gases and dust that are responsible for air pollution (Hossain, 2020; Shihab, 2021), which needs to be investigated for the well-being of the residents and also the co-existence of residential and industrial prospects. Despite Chattogram district being the second most vulnerable city to air pollution after Dhaka (Randall et al., 2015), there has not been a comprehensive trend analysis of pollutants in this area. Hence, our study aims to explore this regard and has selected Chattogram district as our investigation region.

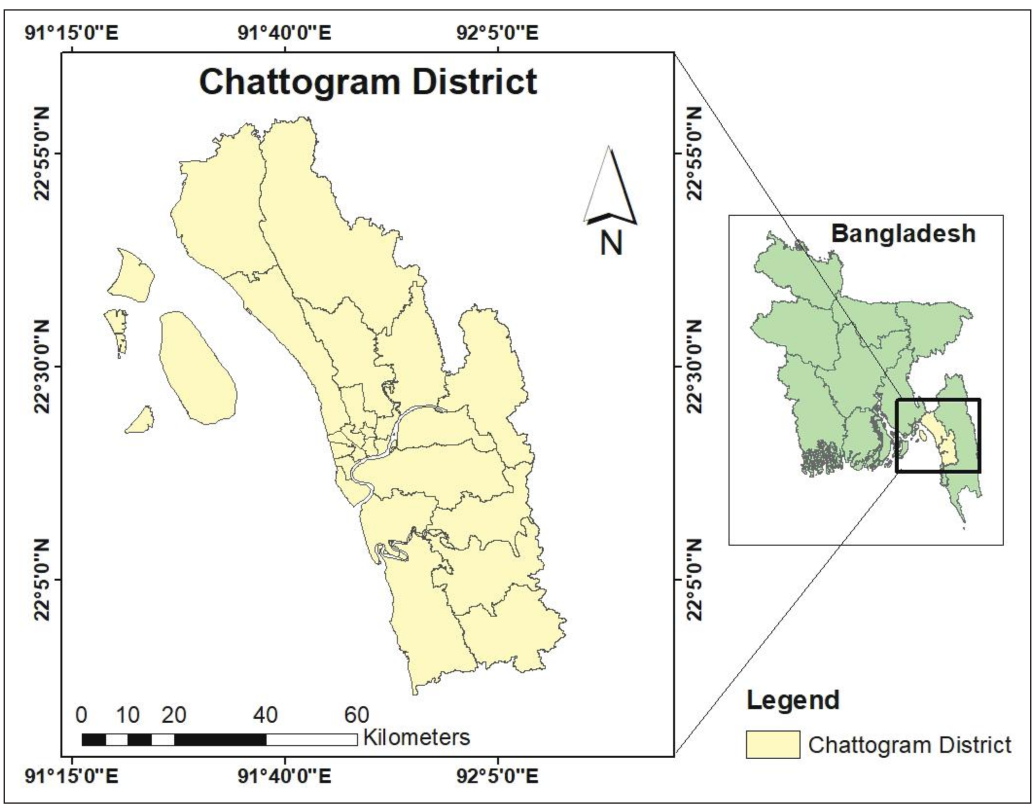

Figure 1: Study Area Map of Chattogram District

MATERIALS AND METHOD

This study employed a mixed-methods research design combining both quantitative and qualitative data collection approaches. The framework aims to assess the impact of seasonal variations on atmospheric pollutants in the Chattogram District, Bangladesh, from 2019 to 2023. The methodological approach integrates remote sensing, secondary data collection from DoE, and community-based surveys and interviews to capture the dynamics of air pollution and its perceived impact on local populations.

Data Collection

Quantitative Method

Air pollution is selected in this research due to its high ability for health damage significantly reducing our life expectancy and its growing impact on public health. There are two methods for assessing the air pollution problem. One is using stationary air pollution measuring instruments and the other is using satellite images. The second method is used in this research. This method is a recent addition to measuring air pollution and it has relatively high precision, provides unique perspectives, and helps to identify high-risk zones. In this research, sentinel 5P TROPOMI satellite images have been used as primary data. The Copernicus Sentinel 5p satellite is dedicated to monitoring the atmosphere carrying the nadir-viewing TROPOMI spectrometer. The satellite was launched on 13 October 2017 and it covers the full surface of the earth within 24 hours. TROPOMI captures images in the electromagnetic spectrum's ultraviolet (UV), visible (VIS), near-infrared (NIR), and shortwave-infrared (SIR) ranges. Thus the images have the ability to detect the concentration of different air components in the vertical components of troposphere; such as Nitrogen dioxide (NO_2, mol/m^2), Sulfur dioxide (SO_2, mol/m^2), Methane (CH_4, ppbV), Carbon monoxide (CO, mol/m^2), Formaldehyde (HCO, mol/m2), Ozone (O3), and also the aerosol pollution index (Morozova et al., 2022). The images give an average value at a spatial resolution of 0.01 arc degree (Cheriyan & Choi, 2020).

Air quality report of DoE in 2018 shows how gaseous pollutants behave in different seasons with a trend typically rising in the dry season and falling in the wet season (Department of Environment, 2018). To see the trend of air pollutants in dry and wet periods in this research, January is chosen as the dry month as minimum air moisture and precipitation are observed in this month. Whereas July is chosen as the wet month. Under the scope of this research, 6 elements of air (SO_2, NO_2, CH_4, CO, HCO, and AAI) were considered. Initially, a total of 60 images of dry seasons and wet seasons of Chattogram from 2019-2023 were targeted for monitoring the seasonal and temporal change of the trace gases' concentration such that for a single element there remain 5 images for dry periods and 5 for wet periods. However, for Methane, suitable images of only the dry period for the years 2019-23 were available for analysis. Thus, a total of 55 images were finally used.

The raw satellite images were collected in tif format using the Google Earth Engine (GEE) platform. This platform is a huge library of satellite images with some analysis capabilities (Cakmak et al., 2023). Necessary images within the target period were collected from the GEE platform using a code (Attached in the Appendix 1). GIS software is used for image processing after downloading the raw images. First of all, the unnecessary background values were removed by setting the 'no data' value as zero from the image properties so that only relevant data points are used for further analysis. Then to compare all images in a standardized value range, the maximum value and the minimum value were noted down manually. Following that the value was substituted after changing the stretch type as maximum minimum. Once, these adjustments were made in ArcGIS software, the processed images were visualized and the spatial patterns of the pollutants could be analyzed across different seasons and years.

Qualitative Method

The produced maps of different seasons and years were then compared to identify the high-concentration zones for each element. Moreover, community surveys and semi-structured interviews of local people and industrial workers were conducted for better understanding and comparison of the trend obtained from satellite image analysis.

Community Surveys: Surveys were administered to local residents living near industrial areas and industrial workers to gather their perceptions of air quality and its effects on their daily lives. Respondents were asked about their experiences with air pollution, especially during dry periods, and any health issues they experienced with poor air quality. The surveys included both closed-ended questions (e.g., a 1–5 scale rating of perceived air pollution) and open-ended questions (e.g., descriptions of health issues, observations of pollution trends).

Semi-Structured Interviews: In-depth interviews were conducted with a subset of industrial workers to explore their insights into factory operations. Questions focused on whether factories adjust operations based on weather conditions (e.g., increased emissions during dry seasons due to higher production levels). These interviews also explored how industrial workers perceived the impact of pollution on their health and the surrounding environment.

A total of 50 respondents were selected through purposive sampling, ensuring representation from diverse areas within Chattogram (industrial, urban, and rural zones). The sample included 30 residents and 20 industrial workers. Face-to-face surveys were conducted to ensure clear responses and gather detailed qualitative data. The respondents were properly briefed about the study objective and the purpose of using their provided data. Informed consent was obtained from all the participants before beginning their interviews regarding further analysis and dissemination of their shared information.

Data Analysis

Descriptive statistics were generated from the survey data, including the average perceived pollution rating, percentage of respondents reporting health issues, and most frequently reported health problems (e.g., respiratory issues). Cross-tabulations were used to compare pollution perceptions between residents and industrial workers. Thematic analysis was performed on interview transcripts to identify recurring themes related to seasonal emission patterns and industrial practices. Both qualitative and quantitative data were integrated to provide a detailed comprehension of air pollution dynamics.

Validation

To ensure accurate insights, the study employed data triangulation by validating satellite and secondary data from the DoE with community surveys and interviews. Satellite-based pollutant levels were compared with the ground-level measurements from the Department of Environment to confirm seasonal trends. Survey responses from residents and industrial workers were aligned with pollution data. Areas with high reported pollution ratings were cross-referenced with satellite and secondary data for consistency.

Data Availability

The sentinel 5P TROPOMI satellite was launched on 13 October 2017 by the European Space Agency and the images for dry and wet periods were accessible from their website. There are two Continuous Air Monitoring Stations (CAMS) operating in Chattogram installed and monitored by the DoE and their data was also accessible upon request.

Table 1: Data Availability Timeframe of Sentinel 5P TROPOMI

Dataset	Data Availability from (in format DD-MM-YYYY)
Aerosol	04-07-2018
CO	28-06-2018
NO_2 / NO	28-06-2018
SO_2	05-12-2018
CH_4	08-02-2019
HCHO	02-12-2018

RESULT AND DISCUSSION

Pollutant Trend Over the Years

Nitrogen Dioxide (NO_2): The trend analysis of satellite images revealed notable seasonal variation in NO_2 concentrations in Chattogram district. In January (in the years 2019, 2021, 2022, and 2023), high-concentration zones were observed in areas like Chattogram Port, Patenga, Anowara, and Hathazari, driven by urbanization and industrial activities (Fig. 2). Elevated NO_2 levels during this period are largely attributed to increased emissions from fossil fuel combustion in transportation and industrial processes, such as petroleum refining, and apparently to the low moisture in the atmosphere. In contrast, July showed a marked decrease in NO_2 levels (Fig. 2) which can be attributed to higher moisture, stronger winds, and better air circulation during the monsoon season (Ahmed et al., 2017). However, 2022 had a higher trend of NO_2 emissions in both January and July, indicating a growing pollution trend.

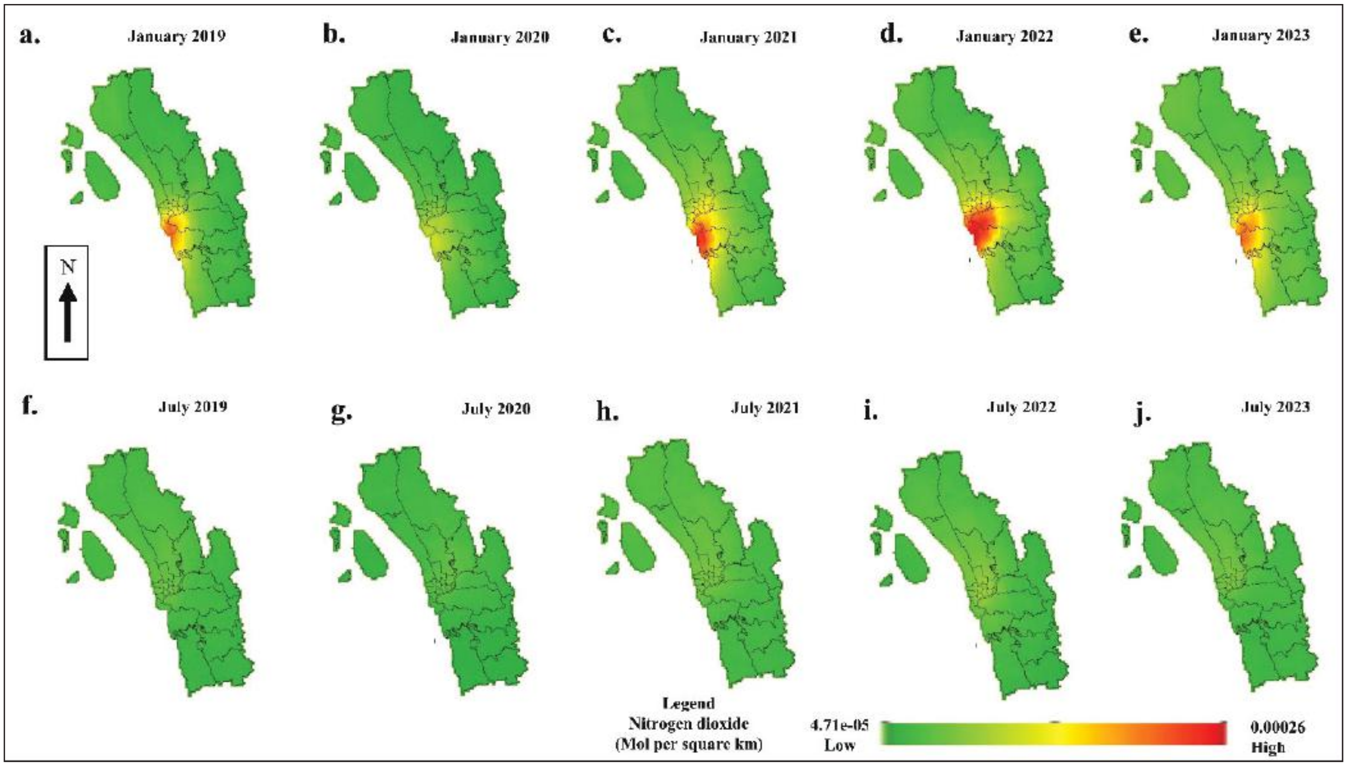

Figure 2: Mean Concentration of Nitrogen Dioxide in January (a) 2019, (b) 2020, (c) 2021, (d) 2022, (e) 2023 and in July (f) 2019, (g) 2020, (h) 2021, (i) 2022, (j) 2023

Sulfur Dioxide (SO_2): The analysis reveals that SO_2 concentrations in July are significantly lower than those in January. Analysis of SO_2 concentrations over the past five years indicates a maximum concentration of 0.000756 mol/m² observed in January 2022 (Fig. 3). Despite this seasonal variation, high-concentration zones remain evident near Raozan, Boalkali, and Rangunia. One plausible reason behind the elevated SO_2 concentrations in this area is the presence of the Raozan Power Plant, a dual-fuel facility predominantly relying on natural gas for power generation. The plant, owned and operated by the Bangladesh Power Development Board (BPDB), is situated on the southern side of the Chattogram-Kaptai Expressway, approximately 25 kilometers northeast of Chattogram city (Energy Transition Bangladesh, 2024; The Independent, 2001). The power plant's operational inefficiencies, coupled with frequent suspensions requiring a minimum of 72 hours for resumption (Energy Transition Bangladesh, 2024), might contribute to inconsistent emissions that elevate localized SO_2 levels. As a major industrial installation in the area, the Raozan Power Plant is suspected to contribute to the persistent SO_2 concentrations observed in the satellite data, particularly during the dry season when atmospheric dispersion is limited. Both oil-fed and gas-fed powerplants have records of acting as uncontrolled emission source of SO_2 in different countries like Iran, India, China, Turkey, etc.(Chakraborty et al., 2008; Nazari et al., 2012; Say, 2006; Zhang & Schreifels, 2011). This underscores the need for further investigation into the power plant's emission control measures and their potential impact on local air quality.

Carbon Monoxide (CO): The trend analysis of Carbon Monoxide concentrations over the years reveals a consistent seasonal variation, with higher levels observed during winter (January) and lower levels during the monsoon season (July). This pattern suggests the absence of a dominant, localized source of CO emissions within the Chattogram district, as the fluctuations appear to be driven primarily by seasonal factors rather than specific, year-round sources. The highest CO concentration was recorded in January 2021, while the lowest was observed in July 2022. In Chattogram, the maximum CO concentration recorded was 0.051 mol/m² (Fig. 4), Notably, the northern part of the Chattogram district exhibited higher CO concentrations during the dry season, particularly in 2021 and 2023.

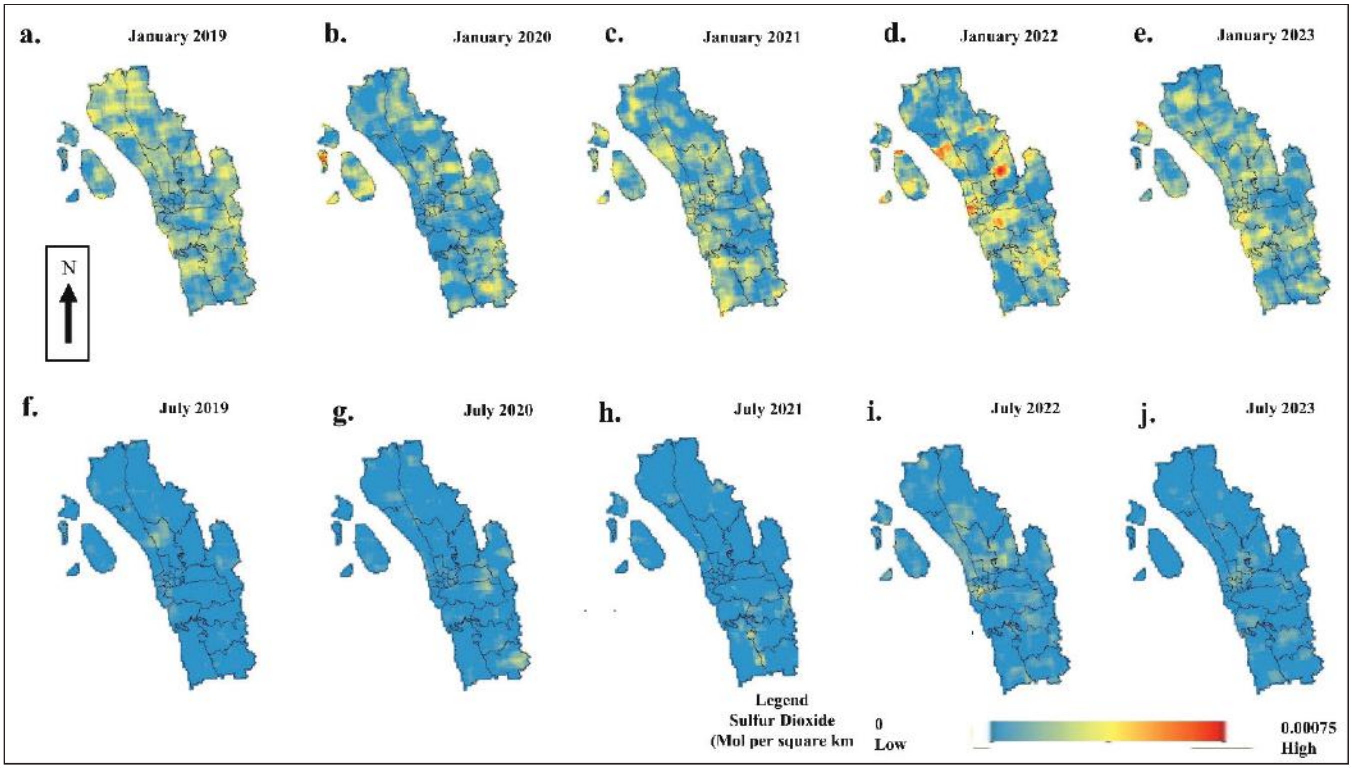

Figure 3: Mean Concentration of Sulfur Dioxide in January (a) 2019, (b) 2020, (c) 2021, (d) 2022, (e) 2023 and 2023 in July (f) 2019, (g) 2020, (h) 2021, (i) 2022, (j) 2023

This area has documented instances of Jhum (shifting) cultivation, which involves the burning of vegetation to prepare land for farming. Although this cultivation practice support local livelihood, it also causes significant amount of green house gases including CO and SO_2 (Lalrinpuii et al., 2023). The elevated CO levels in the northern region of Chattogram may be attributed to emissions from this traditional agricultural practice. The seasonal increase in CO concentrations in northern Chattogram aligns with the timing of these agricultural activities, suggesting a potential link between Jhum cultivation and localized air pollution during the dry season.

Formaldehyde (HCHO): In the analysis of formaldehyde concentrations over the Chattogram district, higher levels were consistently observed in the northern regions, particularly in Mirsharai, Fatikchari, Sitakunda, and Swandip. Unlike other pollutants, the seasonal variation in formaldehyde concentrations between dry (January) and wet (July) months was less pronounced. This could be attributed to ongoing organic matter decomposition and potential agricultural practices that release HCHO throughout the year. The maximum concentration of formaldehyde recorded was 0.00033 mol/m² (Fig. 5). The consistently higher formaldehyde concentrations in the northern part of Chattogram, particularly during the dry season in 2019, may also be related to Jhum cultivation practices. The localized increase of formaldehyde in areas practicing Jhum cultivation suggests a possible link between these activities and elevated HCHO levels. The association of formaldehyde emission with agricultural practices underscores the need for continued monitoring, especially if these activities expand.

Absorbing Aerosol Index (AAI): The Absorbing Aerosol Index (AAI), derived from Sentinel-5 Precursor satellite data, is crucial for detecting UV-absorbing aerosols such as dust and smoke. The AAI is computed by comparing observed and modeled reflectance values, where positive residuals indicate the presence of UV-absorbing aerosols, while negative residuals suggest clouds or non-absorbing aerosols like sulfates. In the case of Chattogram district, the analysis of satellite imagery reveals predominantly negative values, signifying the presence of clouds and non-absorbing aerosols. While dust and smoke are present, their detection has been compromised by excessive cloud cover and moisture. The highest AAI values, 0.007, were recorded in January 2022 and January 2023, reflecting increased dust and smoke concentrations during the dry season.

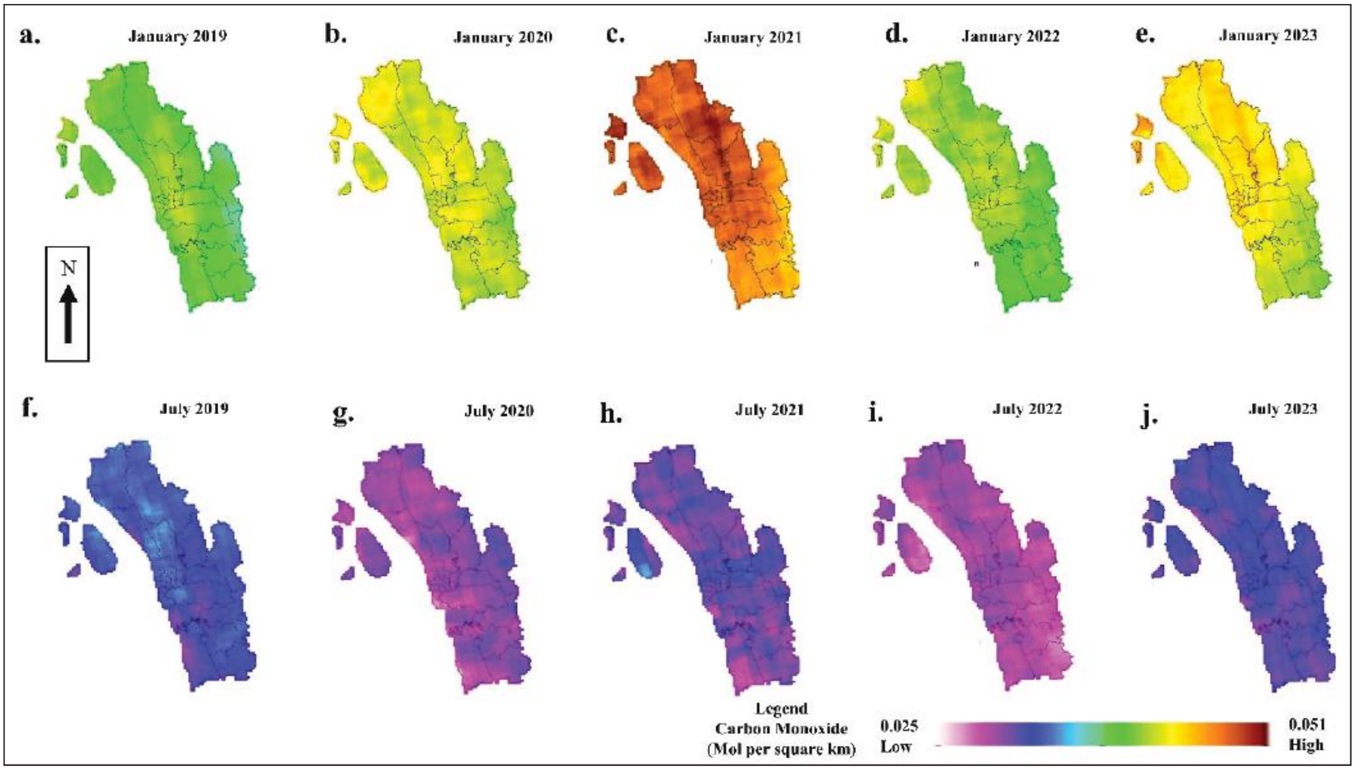

Figure 4: Mean Concentration of Carbon Monoxide in January (a) 2019, (b) 2020, (c) 2021, (d) 2022, (e) 2023 in July (f) 2019, (g) 2020, (h) 2021, (i) 2022, (j) 2023

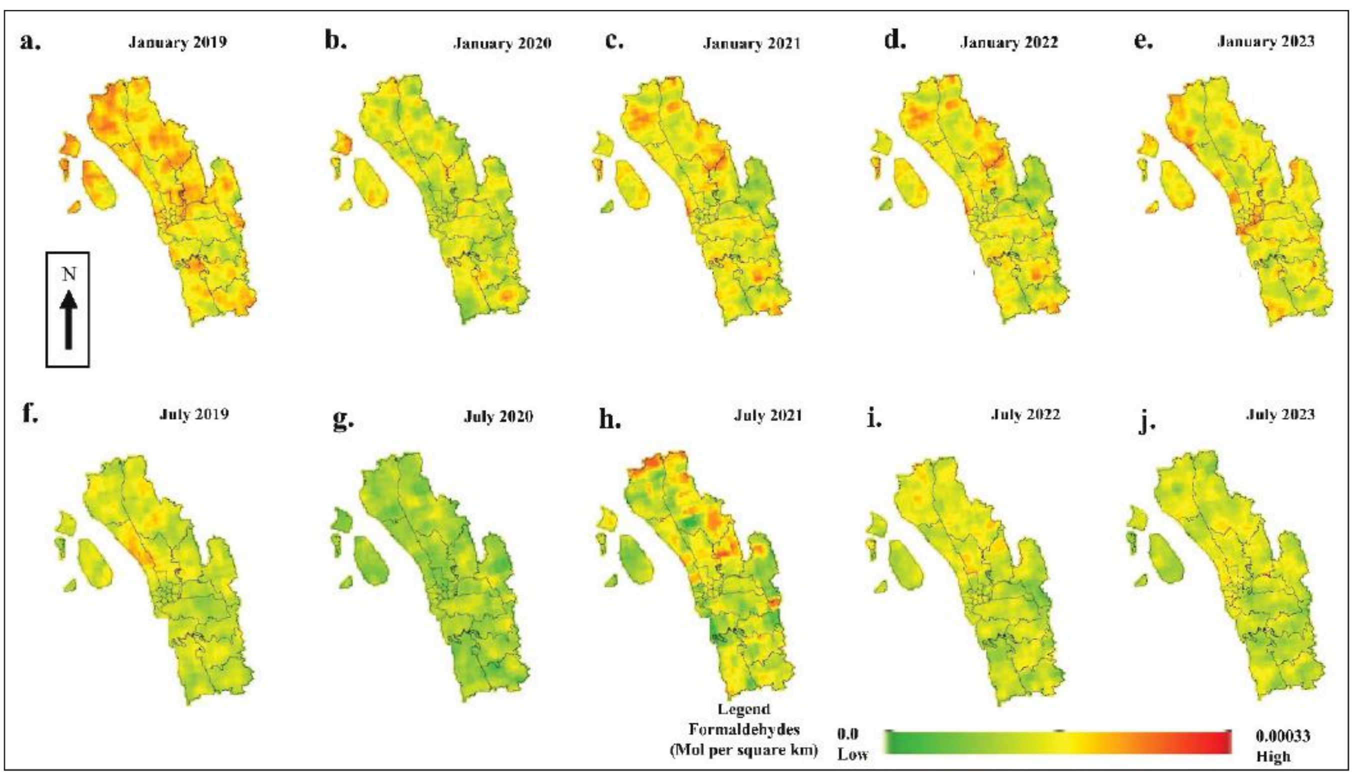

Figure 5: Mean Concentration of Formaldehyde in January (a) 2019, (b) 2020, (c) 2021, (d) 2022, (e) 2023 in July (f) 2019, (g) 2020, (h) 2021, (i) 2022, (j) 2023

In contrast, images from monsoon months such as July predominantly show negative values due to higher moisture levels (Fig. 6). The recent increase in AAI values can be linked to heightened industrial and construction activities in Chattogram, particularly the Eastern Refinery, Bangladesh's largest oil refinery project set to start operations in 2026. This project, along with other large-scale industrial developments, is likely to contribute to the increase in dust and aerosol emissions in the region. Additionally, the effects of the COVID-19 pandemic were evident, with lower residual values in July 2020 and January 2021, corresponding to a reduction in industrial and transportation activities.

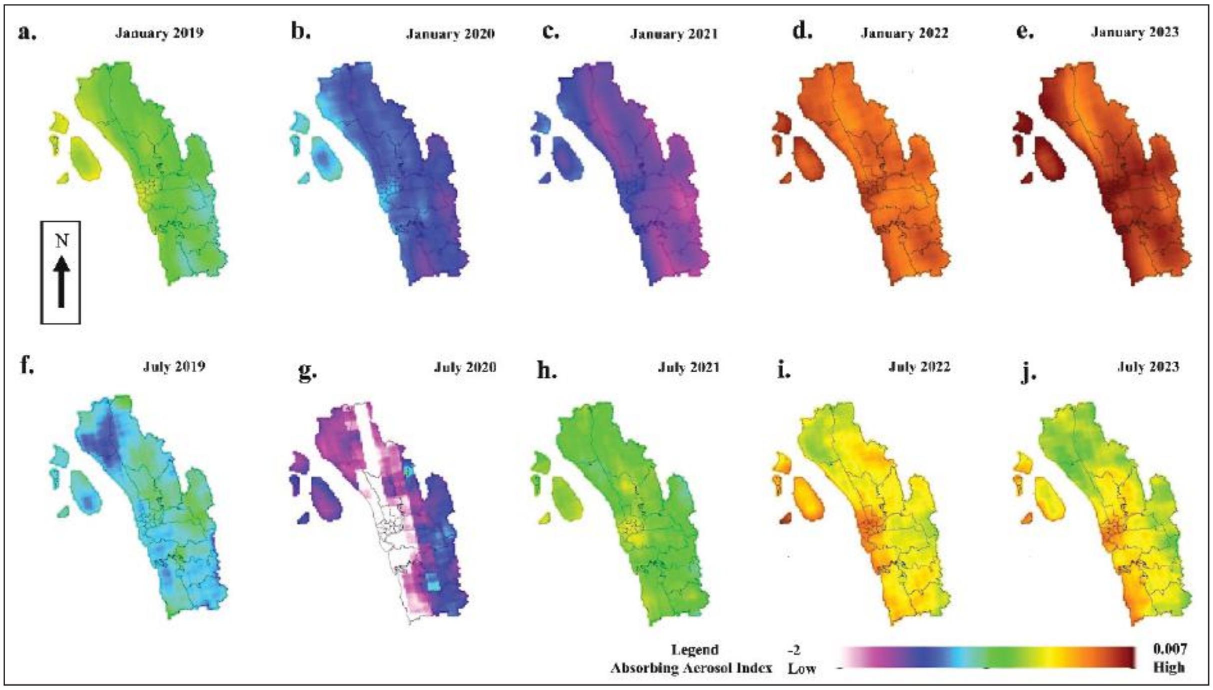

Figure 6: Spatial Mapping of AAI in January (a) 2019, (b) 2020, (c) 2021, (d) 2022, (e) 2023 and in July (f) 2019, (g) 2020, (h) 2021, (i) 2022, (j) 2023

Methane (CH_4): Methane (CH_4) data analysis using Sentinel-5P Precursor satellite imagery reveals notable gaps in pixel values, particularly in the July images. This data inconsistency is primarily attributed to the high moisture levels in the atmosphere during the monsoon season, which hinders the satellite's ability to detect methane via ultraviolet (UV) rays, leading to blank outputs. The missing values in regions where atmospheric moisture prevents accurate methane measurement are recorded in the dataset. Additionally, the first available methane image is from March 2019, not January, since the Sentinel-5P satellite only began providing methane data from February 8, 2019 onwards. Analysis of methane concentrations over Chattogram district shows elevated methane concentrations ranging from 1841 to 2009 ppb (parts per billion) in the highly urbanized and industrialized regions of Chattogram, as marked in the Fig. 7. These values reflect the influence of human activities on methane emissions, particularly in industrial zones. The observed methane (CH_4) concentrations in Chattogram district, ranging from 1841 to 2009 ppb (parts per billion) (Fig. 7), can be compared to typical methane levels in urbanized areas worldwide. Methane concentrations in the global atmosphere are generally within the range of 1800 to 2000 ppb in urban regions, particularly in areas with significant industrial and agricultural activities. Global background methane levels in the atmosphere are around 1870 ppb (as of 2023), according to the World Meteorological Organization (WMO), with natural sources like wetlands and anthropogenic activities contributing to these levels. The observed range in Chattogram (1841-2009 ppb) falls within this global urban range but edges towards the higher end, particularly around industrial hotspots. The peak concentration of 2009 ppb, recorded in Chattogram's more industrialized zones, is higher than typical global averages and signals the influence of local anthropogenic sources like industrial emissions and possibly gas leaks or agricultural activities.

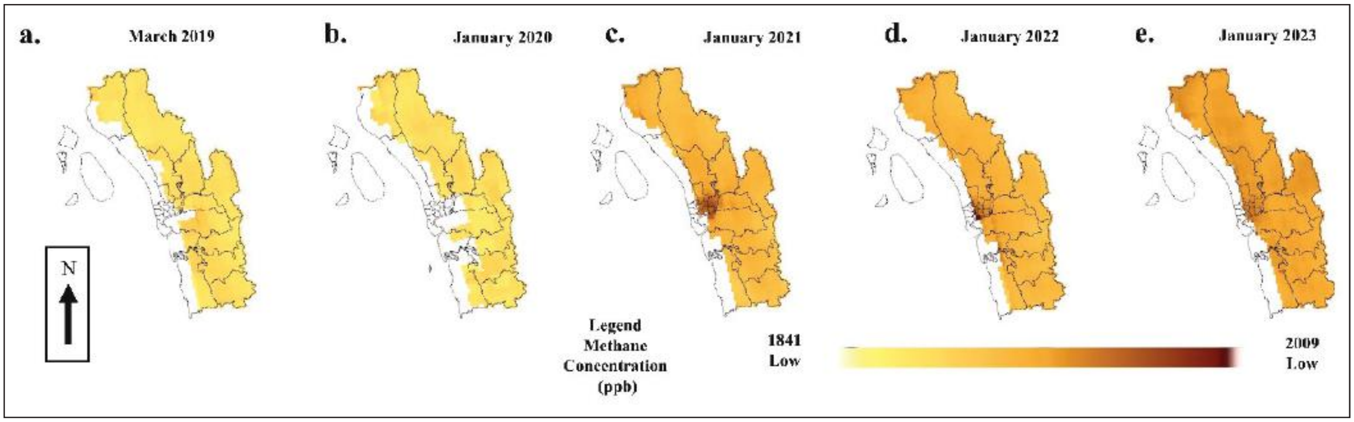

Figure 7: Mean Concentration Mapping of Methane (CH_4) in a) March 2019 and in January b) 2020, c) 2021, d) 2022, e) 2023

Overall, the pollutants exhibited growing trends in general over the year. Other than Formaldehyde and Methane, the peak concentrations of the gases were recorded in the dry periods while their values lowered during the wet period. While industrial activities, vehicle circulation, and traditional agricultural activities like Jhum cultivation are important factors, the low moisture and reduced wind dispersion in the atmosphere during winter presumably contribute to the higher concentration of pollutants. Moreover, clouds and rainfall are more likely to wash away dust and reduce concentration of the atmospheric pollutants during the wet seasons. These justifications align with other research based on Chattogram where industries, automobiles, power plants, construction sites, and burning biomass among other sources have been recognized as primary sources of pollutant emission (Jubaer et al., 2022). In addition, atmospheric factors like weaker wind speed, irregular rainfall, and lower ambient temperature in the dry winter period have been found to be contributing to the increase of the mass concentration of pollutants in the atmosphere (Hoque et al., 2022). The urban and industrialized zones particularly around Chattogram port, Raujan powerplant, and northern areas prominently show higher concentrations of atmospheric pollutants. The condition is suggestive of discomfort and health implications like respiratory diseases and chronic illness among the residents and industrial workers around the areas.

Table 2: Overview of the Analazyed Pollutants in Chattogram District

Name	Hotspot	Primary Sources	Seasonal Trend	Key observations
NO_2	Chattogram Port, Patenga, Anowara, Hathazari	Fossil fuel combustion in transportation and industries	Higher in January, lower in July	Year-round elevated levels in the year 2022 indicate a growing pollution trend.
SO_2	Raujan, Boalkhali, Rangunia	Power plants	Higher in January, lower in July	Persistent higher concentration around power plants implies industrial emission.
CO	Northern Chattogram	Jhum cultivation and seasonal biomass burning	Higher in January, lower in July	Higher levels in January can be associated with agricultural activities during dry seasons.
HCHO	Mirsharai, Sitakunda, Fatikchari, Swandip	Organic matter decomposition and agricultural practice	Minimal seasonal variation	High concentrations may be linked to Jhum cultivation and maximum levels were recorded in 2019

AAI	Urbanized/ Industrialized zones	Dust, smoke, industrial or construction activities	Higher in January, negative values in July (for clouds/ moisture effects)	Peaks in 2022 and 2023 due to industrial expansion, especially the Eastern Refinery zone. Lower residual values in July 2020 and January 2021, showing a reduction in industrial and transportation activities due to COVID-19
CH_4	Urbanized/ Industrialized zones	Natural gas use, agricultural activities, landfills	Data unavailability for July (due to high moisture)	Concentrations edge towards the higher range of the global urban averages and their values peak near industries.

Perceived Air Pollution of the Locals

A field survey was conducted with 50 respondents, consisting of 30 residents and 20 industrial workers from various areas within Chattogram, including industrial, urban, and rural zones. The survey aimed to validate remote sensing data on air pollution, focusing on the perception of changes in air quality, seasonal variations, and associated health impacts. The data was analyzed using descriptive statistics, cross-tabulation, and inferential statistics to explore the relationship between occupation, area of residence, and the perceived impact of air pollution.

Demographic Profile of Respondents

The sample included a diverse range of respondents. 60% (30) were residents, while 40% (20) were industrial workers, ensuring representation from both community members and those working in high-pollution areas. Participants came from three distinct geographic zones: industrial (40%), urban (30%), and rural (30%).

The age distribution showed that 30% of respondents were between 18-30 years old, 40% were in the 31-45 age group, and 20% were aged 46-60. 10% were older than 60. In terms of gender, the sample was balanced, with 52% male and 48% female respondents. Regarding their time spent in the area, 35% had lived or worked in the area for 6-10 years, 30% had been in the area for 1-5 years, and 25% had lived or worked in the area for more than 10 years. The remaining 10% had been there for less than a year (Fig. 8).

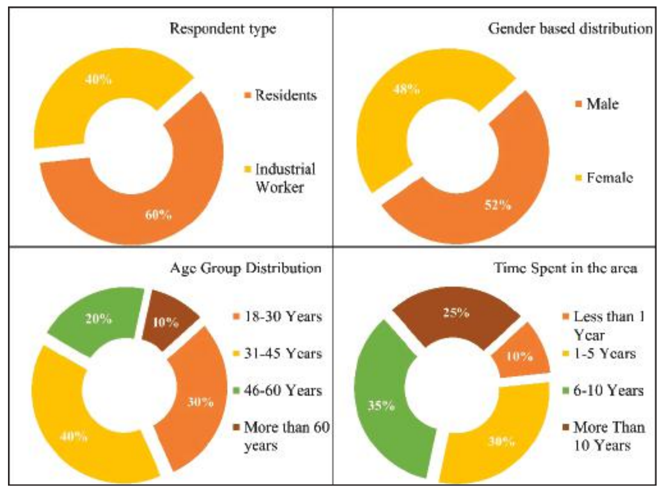

Figure 8: Demographic Profiling of Respondents

Perception of Air Quality Over Time

The majority of respondents perceived a significant deterioration in air quality over the past five years. Of the 50 respondents, 40% (20) reported that air quality had greatly worsened, and 30% (15) felt that it had somewhat worsened. , 20% (10) reported no change in air quality, and only 10% (5) observed some improvement. A breakdown by occupation revealed that 50% of industrial workers reported that air quality had greatly worsened, compared to 35% of residents. The respondents from key industrial zones in Chattogram reported a perceived increase in air pollution during the dry season, which aligned with satellite data showing higher concentrations of NO_2, SO_2, CO and AAI during the same period. The residents living in high-concentration zones perceive air pollution as a significant threat to their health and well-being. Many respondents attribute the elevated pollution levels to the industrial activities in the area, particularly those associated with the Raujan Power Plant and other nearby industrial setups. This perception aligns with the data indicating the concentration of SO_2 in these regions, reinforcing the community's concerns regarding the impact of industrialization on air quality. Respondents in the high-concentration zones also testified to increased levels of dust and smoke during the dry season over the past five years. Many linked this rise in pollution to ongoing industrial and construction projects, supporting the satellite observations. In the survey, 35% of residents reported a somewhat worsened perception of air quality, while 25% noted no change (Table 3). These respondents from specific rural locations reported less significant pollution impacts which corresponds with low-concentration zones in the satellite data, adding further confidence to the accuracy of the spatial distribution patterns.

Table 3: Cross-Tabulation of Perception of Air Quality

Occupation	Greatly Worsened	Somewhat Worsened	No Change	Improved
Industrial Worker	50% (10)	35% (7)	5% (1)	10% (2)
Resident	35% (10)	25% (8)	25% (8)	15% (4)

Seasonal Variation in Air Pollution

The integration of community perceptions and satellite data revealed high consistency with these seasonal air pollution trends observed in TROPOMI data. A significant seasonal pattern was observed, with 70% (35) of respondents indicating that air quality was worse during the dry season, compared to only 10% (5) who believed that air quality was worse during the rainy season. 15% (7) felt there was no seasonal difference, while 5% (3) were unsure. A paired t-test was conducted to compare perceived air quality between the dry and rainy seasons. The mean score for air pollution in the dry season was 4.3 (on a 5-point scale), compared to 2.7 for the rainy season. The difference was statistically significant ($t = 5.12$, $p < 0.01$), confirming that air pollution is perceived to be significantly worse during the dry season. These findings align closely with satellite observations, which showed consistently higher concentrations of pollutants during the dry season across all years analyzed (2019–2023).

Relationship Between Occupation and Perception of Air Quality

A Chi-Square test was performed to examine the relationship between occupation and the perception of worsening air quality. The chi-square test results show a chi-square value of 4.35 with 3 degrees of freedom and a p-value of 0.22 (Apendix 2). Since the p-value is greater than 0.05, we fail to reject the null hypothesis, indicating that there is no statistically significant difference between the perception of air quality among industrial workers and residents. The expected and observed frequencies for both groups are relatively close, suggesting that the occupation does not significantly influence the perception of air quality. Therefore, the test suggests that both industrial workers and residents share similar perceptions of air quality, at least at the 5% significance level.This convergence of qualitative perceptions, statistical analyses, and remote sensing trends strengthens the validity of the findings and underscores the complementary role of community-based surveys in enhancing satellite-based air quality assessments.

Remote sensing data from TROPOMI primarily captures the total column concentration of pollutants in the troposphere, which represents the vertical distribution of pollutants from the surface to higher altitudes. While this differs from direct ground-level measurements, there is often a strong correlation between tropospheric concentrations and surface-level air pollution, particularly in regions with high pollutant emissions. This is because many air pollutants are primarily emitted from ground-level sources like industrial activities, vehicles, and biomass burning, and their concentrations near the surface tend to dominate the overall tropospheric column (Grzybowski et al., 2023; Rudke et al., 2023; Savenets et al., 2022).

Validation

The validation of satellite-derived air pollution data from TROPOMI is performed using ground-based secondary data collected from the DoE, Bangladesh. The study dealt with atmospheric pollutant data for six key parameters: Nitrogen Dioxide (NO_2), Sulfur Dioxide (SO_2), Methane (CH_4), Carbon Monoxide (CO), Formaldehyde (HCHO), and the Absorbing Aerosol Index (AAI) from TROPOMI (Time-frame 2019-2023). However, the ground-based measurements from the Continuous Air Monitoring Stations (CAMS) in Chattogram are limited to SO_2, NO_2, PM2.5, and PM10 (Time-frame 2021-2023). This difference in parameters (exclusion of HCHO, CH_4, CO), the limited coverage of CAMS stations (only two stations), alongside the restrictive timeframe (access provided by DoE) create challenges in validation but still allow for significant comparison of temporal, and especially seasonal trends.

The CAMS data utilized for validation in this study is derived from two monitoring stations in Chattogram. The first station, CAMS-6, located at the TV Station in Khulshi (Lat: 22˚ 21′ 38.79″ N Long:91˚ 47′ 52.81″ E), is positioned in an urbanized residential area. This station is equipped with an inlet height of 4.8 meters and a meteorological tower height of 7 meters, ensuring accurate collection of pollutants. The second station, located in Agrabad (Lat: 22˚ 19′ 21.39″ N, 91˚ 48′ 04.10″ E), operates in a highly urban area. Its inlet and meteorological tower heights are 8.8 meters and 11 meters, respectively (GoB, 2024). Together, these two stations provide critical temporal ground-based data for validating the satellite-derived results. Although TROPOMI data is presented in column density units (mol/m²) and CAMS data measures ground-level concentrations (ppb for SO_2 and NO_2, µg/m³ for PM2.5 and PM10), the temporal trends in pollutant levels observed by both datasets show strong alignment. This qualitative agreement validates TROPOMI's ability to capture seasonal and temporal variations in air pollution, despite differences in measurement units and spatial coverage. Converting column densities (mol/m²) to ground-level concentrations (ppb) may introduce significant inaccuracies because such a conversion requires detailed information about vertical pollutant distribution, atmospheric pressure, temperature, and altitude, which vary across time and space. Without this complex vertical profile data, any conversion would oversimplify the atmospheric dynamics and could lead to unreliable results (Wang et al., 2022).

The validation of SO_2 and NO_2 derived from TROPOMI (in mol/sqm units) shows a strong temporal alignment with the CAMS measurements (in ppb). For instance, during peak industrial activities in the dry season, particularly in January 2022, CAMS recorded elevated SO_2 concentrations, reaching 52.7 ppb. Similarly, satellite-derived SO_2 data from TROPOMI confirmed these peaks, capturing elevated levels in the tropospheric column. In contrast, during the monsoon period, CAMS data indicated significantly lower SO_2 concentrations, such as 2.3 ppb in July 2022, a pattern that was mirrored in the satellite observations. A similar trend is observed for NO_2. The CAMS measurements recorded a notable increase in NO_2 concentrations during January 2022, peaking at 115.2 ppb, which coincided with the elevated NO_2 levels detected by TROPOMI (Table 4). During the wet period, CAMS data revealed a reduction in NO_2 concentrations, such as 3.6 ppb in July 2022 (Table 4), reflecting seasonal variations that were similarly captured in the satellite-derived measurements. The consistency between the ground-based and satellite data validates the reliability of Sentinel-5P in monitoring tropospheric SO_2 and NO_2 trends.

In addition to SO_2 and NO_2, the CAMS measurements for PM2.5 and PM10 provide complementary information for validating the satellite-derived Absorbing Aerosol Index (AAI) since PM2.5 and PM10 comprise aerosol (Asimakopoulos et al., 2012). PM2.5 and PM10 represent particulate matter concentrations at ground level, which are directly influenced by industrial emissions, vehicular pollution, and construction activities (Pekey et al., 2010; Srimuruganandam & Nagendra, 2010). In January 2022, CAMS data recorded extremely high PM2.5 values, reaching 693.5 µg/m³, and PM10 values of 373.8 µg/m³ (Table). These spikes were primarily attributed to the accumulation of pollutants during the winter months, when reduced atmospheric dispersion exacerbates pollution levels. TROPOMI-derived AAI, which measures the presence of absorbing aerosols like black carbon and dust in the vertical column, also indicated elevated aerosol loads during the same period. Although PM2.5 and PM10 represent surface-level particulate concentrations, their alignment with AAI provides a more holistic understanding of atmospheric pollution dynamics.

The validation process highlights some limitations that must be considered. The CAMS measurements do not include methane (CH_4), carbon monoxide (CO), or formaldehyde (HCHO), which are important parameters provided by TROPOMI. The lack of ground-based data for these pollutants restricts comprehensive validation for all TROPOMI parameters. Furthermore, the spatial coverage of the CAMS stations is limited to only two locations in Chattogram, which restricts the validation process to temporal comparisons rather than spatial assessments. Despite these limitations, the strong alignment of SO_2, NO_2, PM2.5, and PM10 trends between the ground-based and satellite-derived data confirms the reliability of TROPOMI in capturing seasonal and temporal variations in air pollution.

Table 4: CAMS-Based Measurements of Selective Atmospheric Pollutants in Chattogram

	SO2 (ppb)			NO2 (ppb)			PM 2.5 (μg/m³)			PM10 (μg/m³)			Station
	Min	Max	Avg	Min	Max	Avg	Min	Max	Avg	Min	Max	Avg	
Jan 2021	0.5	14.9	1.9	16.3	79.8	27.5	30.6	441.6	83.9	135.4	670.3	208.7	Agrabad (Lat: 22° 19´21.39´N, Long:91° 48´04.10´E)
July 2021	14.6	16.6	15.0	6.0	77.6	8.8	5.0	98.3	10.5	14.9	406.8	30.0	
Jan 2022	16.8	52.7	18.4	1.2	115.2	21.6	4.0	565.0	693.5	103.3	565.8	373.8	
July 2022	1.8	8.6	2.3	0.8	26.3	3.6	3.1	76.0	42.9	32.2	157.0	141.3	
Jan 2023	5.4	8.1	6.1	4.8	73.4	16.8	107.6	914.8	234.3	185.8	899.6	292.9	
July 2023	5.6	11.9	5.9	0.8	55.7	4.8	4.1	861.9	33.6	25.3	836.4	67.5	
Jan 2021	0.5	39.9	4.9	0.9	19.1	3.5	70.6	511.7	127.2	97.7	500.0	173.5	Khulshi (Lat: 22° 21´38.79´N Long:91° 47´52.81´E)
July 2021	0.3	39.9	4.3	0.3	46.6	8.7	6.9	241.8	11.4	12.4	369.4	19.9	
Jan 2022	0.3	16.3	3.3	3.5	29.8	8.6	14.3	287.1	78.5	118.4	376.5	161.6	
July 2022	1.8	60.4	4.4	2.5	24.6	11.5	6.4	227.3	16.8	13.6	289.8	30.9	
Jan 2023	1.3	725.0	3.6	1.1	14.0	10.4	54.3	424.0	98.3	NDA	NDA	NDA	
July 2023	3.0	668.2	13.6	0.6	11.1	375.2	3.8	121.9	9.0	21.4	94.3	33.1	

Hence, the comparison of Sentinel-5P TROPOMI satellite data with ground-based CAMS measurements demonstrates significant temporal consistency for SO_2, NO_2, PM2.5, and PM10. The trends observed in CAMS data, particularly during dry and wet periods, validate the satellite-derived results, emphasizing the potential of remote sensing technologies for air quality monitoring. The inclusion of PM2.5 and PM10 data further complements the Absorbing Aerosol Index by linking ground-level particulate matter concentrations with atmospheric aerosol loads. While the limited pollutant coverage and spatial constraints of CAMS present challenges, the validation process establishes the reliability of Sentinel-5P for monitoring air quality dynamics in industrialized regions.

CONCLUSIONS

Slow-onset disasters like air pollution do not receive ample attention in Bangladesh though it is an alarming issue worldwide and can seriously threaten the environment and public health. Despite the growing exposure to air pollution, not sufficient research about the air quality of all megacities of the country other than the capital has been conducted. Chattogram, considered as the "Financial capital of Bangladesh" is home to lots of industries and it is a crucial zone contributing to the country's economic development. So it has been the study area for our research. In this study, air pollutant concentration has been assessed using sentinel 5P TROPOMI satellite images for better temporal and spatial resolution which is important because the concentration in the atmosphere changes with the change of temperature and seasonal patterns. In addition, the obtained data has been compared with the ground-based measurements of two CAMS stations in Chattogram for comparing consistency and reliability. It reveals a significant comparison between the dry and wet period concentrations of NO_2, SO_2, CO, and dust particles, especially in urbanized and industrial areas. Formaldehyde's concentration is higher in the northern highland region of Chattogram district. These damaging substances rose in dry periods across large areas.

Chattogram is exposed to air pollution as it has a higher number of industries, oil refineries, and brick kilns that consume fossil fuel and are sources of greenhouse gas emissions. Also, increasing the concentration of several pollutants is attributed to forest fires during Jhum cultivation. It is observed that due to lower industrial production and fewer vehicle emissions during the COVID-19 pandemic, AAI levels declined. Overall, the concentration of dust particles has significantly increased in recent years (2022, 2023) compared with the previous 3 years especially in urban areas near the Chattogram Seaport because of the past and post-COVID-19 era showing an increasing trend over the years which can be a threat in the future. Another observation from the qualitative research was that the industrial workers perceived the deterioration of air pollution as more prominent than the people residing around the industrial area.

Using satellite images in this study opened up many dimensions that can be used in the future, with the help of ground truthing, where the pollutant sources can be identified. Limitations in this research included the effect of high humidity and clouds on the satellite images which created difficulty in collecting methane data. To complement the quantitative data, cross-verification, and qualitative field surveys have been done. Incorporating Ground-based validation has enhanced the data accuracy and reliability. This method can also be used for other industrial areas in Bangladesh. The research outcomes depict the trend of pollutants in Chattrogram and emphasize the urgency of mitigating pollutant emissions and continuous monitoring of air quality in industrialized regions like Chattogram. During the dry period, public awareness should be more regarding air pollution. Coordinated approaches between the government and private initiatives together can build a healthier and sustainable environment for future generations.

DECLARATIONS

Conflict of Interest: The authors declare no competing interest.

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APPENDIX

Appendix 1

Google Earth Engine Code for image download and collection

```
var dataset = ee.ImageCollection("COPERNICUS/S5P/OFFL/L3_CH4")
var image = dataset.filterBounds(table)
        .filterDate('2023-07-01' , '2023-07-31')
        .select('CH4_column_volume_mixing_ratio_dry_air')
        .mean()
        .clip(table)
var band_viz = {
  min: 0.0,
  max: 0.0005,
  palette: ['black', 'blue', 'purple', 'cyan', 'green', 'yellow', 'red']
};
Map.addLayer(image , band_viz)
Map.centerObject(table,10)
Export.image.toDrive({
  image:image,
  description:'CH4_01-31_July_2023',
  folder: 'Air_Quality_CH4',
  scale: 1113.2,
  maxPixels: 10000000000000,
  region: table,
  fileFormat: 'GeoTIFF'
})
```

Appendix 2

Perception of Air Quality	Industrial Worker (Observed)	Resident (Observed)	Industrial Worker (Expected)	Resident (Expected)	$\frac{(O-E)^2}{E}$ (Industrial)	$\frac{(O-E)^2}{E}$ Residents
Greatly Worsened	10	10	8	12	0.5	0.3333
Somewhat Worsened	7	8	6	9	0.1667	0.1111
No Change	1	8	3.6	5.4	1.8778	1.25
Improved	2	4	2.4	3.6	0.0667	0.0444
Total	20	30			2.6102	1.7388

Total chi-square value, $x^2 =$ 2.6102+1.7388=4.35

The degree of freedom, df=(4−1)×(2−1)=3, p-value=0.22