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Expository Assessment of Air Quality Scenario with Sentinel-5 Precursor TROPOMI Explorer Sensor

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ABSTRACT

Air pollution is the atmospheric state in which the concentration of specific elements has adverse impacts on human health as well as the environment, including global warming, transportation disruptions, acid rain, and ozone layer depletion. Nowadays, a large portion of the world's population lives in urban areas, where population growth and the increasing number of vehicles have significantly worsened air quality. Clean air is essential for the health and well-being of any region's environment and its inhabitants. Henceforth, the primary focus of this research endeavor is to meticulously scrutinize the levels of key air pollutants, notably nitrogen dioxide (NO_2) and sulfur dioxide (SO_2), leveraging satellite remote sensing data obtained from TROPOMI EXPLORER across a network of monitoring stations dispersed throughout Lucknow City. Additionally, it aims to meticulously dissect ground-based air quality monitoring data to validate and amalgamate the observations derived from satellite technology. Furthermore, it analyzes the distribution of concentrations of primary air pollutants, encompassing NO_2, SO_2, and PM_{10}, within Lucknow City, juxtaposing them against the stringent benchmarks stipulated by the World Health Organization (WHO) for air quality standards. Moreover, it endeavors to ascertain the deleterious health ramifications of air pollution by correlating air quality metrics with health outcomes among the denizens of Lucknow City through a meticulously crafted questionnaire survey. The scrutiny of satellite imagery unveiled a conspicuous escalation in the concentration of air pollution parameters vis-à-vis the WHO's prescribed thresholds, portending consequential adverse ramifications for both the environment and human health.

INTRODUCTION

In Indian megacities, Lucknow is one of the most polluted with respect to particulate pollution. Due to this, air pollution has emerged as a serious environmental challenge, especially in urban areas. According to the World Air Quality Report 2019, Lucknow ranks 11th for poor air quality among the top 15 most polluted cities worldwide (IQ Air 2019). The major sources of air pollution in Lucknow include urbanization, industrialization, vehicular exhaust, construction work, and burning activities (Bharti et al. 2017, Kumar & Dwivedi 2021). As a result of the increasing pace of anthropogenic activities, Lucknow has become one of the most polluted cities in the world, especially in the winter season.

Air pollution means the contamination of air. In the Air (Prevention and Control of Pollution) Act, 1981, section 2(a), air pollution is characterized as "any solid, liquid, or gaseous substance (including noise) present in the atmosphere in such concentration as may be or tend to be injurious to human beings or other living creatures or plants or property or the environment" (Government of India 1981). Over the past two decades, there has been a significant increase in urbanization and industrialization in many Indian cities. This urbanization has had both positive and negative effects on air quality in cities worldwide. Various chemicals, whether from natural or man-made sources, continuously enter the atmosphere and interact with the environment, causing diseases, pollution, and environmental degradation; these substances are known as pollutants. Both developed and developing countries are striving to balance climate issues with economic development. There is a strong correlation between population growth and environmental contamination, with environmental damage escalating as the population increases (Barck et al. 2005). Poor environmental conditions adversely affect the biological sections of ecosystems.

In Asia, air pollution has worsened with the progression of industrialization and urbanization. In Lucknow, studies on air pollution have primarily focused on atmospheric pollution (Barman et al. 2010, Pandey et al. 2012, 2013, Kim 1992). Geographical Information System (GIS) technology is extensively used to assess, inventory, identify, model, and manage the natural environment. Air pollution, a major environmental issue, is concentrated in urban areas. Burning fuel releases particulate matter and diverse types of unburned or waste oil into the environment (Khan et al. 2010).

Analyzing air pollution, particularly regarding Respirable Suspended Particulate Matter (RSPM), is a significant challenge. According to a WHO report, particulate matter (PM_{10}) affects more people than any other air pollutant. Even low levels of PM_{10} have been associated with adverse health effects (Agarwal 2012). As modern research continues to uncover the health impacts of tiny particles and pollutants, the issue of particulate matter and gaseous emissions in the atmosphere is gaining increased attention.

Lucknow, the most populous city, and capital of Uttar Pradesh, is the second-largest city in northern and central India. It is one of India's fastest-growing metropolitan areas, rapidly emerging as a hub for manufacturing, business, and retail. Air pollution contributes to many outstanding environmental issues and human health risks, triggering a substantial mortality rate affecting developed and developing countries worldwide (Sinha et al. 2013, Saber et al. 2020, Biswas et al. 2020, Filonchyk 2022). Air pollution includes particulate matter ($PM_{2.5}$ and PM_{10}), nitrogen oxide and dioxide (NO, NO_2), sulfur dioxide (SO_2), carbon monoxide (CO), and ozone (O_3). The WHO defines air pollution as the contamination of indoor and/or outdoor environments through chemical, physical, or biological factors that cause changes in the normal features of the ambient air. Additionally, the World Health Organization (WHO) announced that air pollution kills millions worldwide every year. Industrial areas worldwide are considered the main contributors to air pollution and are responsible for deteriorating human health (Salman et al. 2021).

The Air Quality Index (AQI) of Lucknow is adopted through the Central Pollution Control Board to provide information on the levels of air pollutants. Table 1 shows air quality guidelines established by the WHO and CPCB.

Several authors utilized in-situ ground measurements and TROPOMI/Sentinel-5P high spatial-resolution images to study and monitor the nitrogen dioxide (NO_2) levels in the ambient air, including Zhao et al. (2020), Shikwambana et al. (2020), Lalongo et al. (2020), Vîrghileanu et al. (2020), and Al-Alola et al. (2022). These studies suggested using TROPOMI/Sentinel-5P images only to monitor the NO_2 concentration. Lalongo et al. (2020) suggested using TROPOMI images with NO_2 observations collected from ground-based measurements.

Theys et al. (2021) examined the SO_2 emissions using Sentinel-5P data obtained during 2019. The authors found biases in the SO_2 emissions using TROPOMI data due to surface-related effects such as elevated terrain and albedo. Opio et al. (2021) utilized TROPOMI to monitor the sulfur dioxide (SO_2) over East Africa. The results of the analysis revealed an increasing trend in SO_2. Anil and Alagha (2021) studied CO, SO_2, NO_2, O_3, and PM_{10} in the Eastern Province using data collected from the General Authority of Meteorology and Environment Protection during the COVID-19 lockdown. The study encompassed monitoring stations in Jubail, Qatif, Dammam, and Al Ahsa. It was observed that the concentrations of NO_2, SO_2, CO, and PM_{10} decreased at certain stations to levels below the WHO standards. Conversely, O_2 concentrations increased at most of the stations. Farahat (2016) examined dust events, SO_2, and NO_2 in the Arabian Peninsula, including the United Arab Emirates, Qatar, Kuwait, Oman, Bahrain, and Saudi Arabia. The study in Saudi Arabia concentrated on the cities of Taif, Jeddah, and Mecca. The findings indicated that NO_2 tropospheric column density was high and SO_2 concentrations exceeded the WHO guideline mean values in these major cities.

The project aims to analyze the levels of key air pollutants, such as nitrogen dioxide (NO_2) and sulfur dioxide (SO_2), utilizing satellite remote sensing data (TROPOMI Explorer) collected from various stations across Lucknow City. Additionally, it involves the examination of ground-based air quality monitoring data to validate and integrate the observations obtained from satellites. The project will compare key air pollutant levels (NO_2, SO_2, and PM_{10})

Table 1: Mean concentration standards and AQI of primary air pollutants.

Pollutants	Average Time period	WHO [$\mu g.m^{-3}$)][a]	CPCB[$\mu g.m^{-3}$][b]
PM_{10}	24- h	45	60
NO_2	24- h	25	40
SO_2	24- h	40	50

obtained from CAAQM stations of CPCB and UPPCB with WHO standards. Furthermore, the project intends to evaluate the health impacts of air pollution by conducting surveys among residents of Lucknow City and correlating air quality indicators with health outcomes.

MATERIALS AND METHODS

Study Site Description

Lucknow, the capital of the state of Uttar Pradesh, India, is located in northern India between 26°85′ N latitude and longitude 80°95′ E. Lucknow lies at the upper Gangetic plains of India, 123m (404 ft) above sea level (Sen 2017); experiences a great variation in temp (45°C in summer and 5°C in winter) and average rainfall is 100 cm (Singh et al. 2017). Fig. 1 shows the study area.

Air Quality Data

For this study, air quality data were obtained from Continuous Ambient Air Quality Monitoring (CAAQM) stations operated by the Central Pollution Control Board (CPCB) and the Uttar Pradesh Pollution Control Board (UPPCB). In Lucknow, six monitoring stations located in various areas (industrial, commercial, and residential) continuously monitor air pollutants daily (Table 2).

Satellite Data

Multiple spatial and temporal data types and sources were collected for monitoring the air pollutant parameter as shown in Table 3.

Table 2: List of Monitoring Stations.

Station Name	Monitoring Station	Latitude	Longitude
B R Ambedkar University	MS 1	26.8632	80.90845
Gomti Nagar	MS 2	26.850017	80.9833163
Kendriya Vidyalaya	MS 3	26.9004194	80.9484125
Kukrail Picnic Spot-1	MS 4	26.8632	80.90845
Lalbagh	MS 5	26.165998	80.970673
Talkatora District Industries Center	MS 6	26.840503	80.8792761

Access to Sentinel-5P (Tropomi Explorer) satellite data has been obtained. The application has been launched and ensured its latest data is available. Relevant atmospheric composition data, including measurements of pollutants like nitrogen dioxide (NO_2) and sulfur dioxide (SO_2), is being acquired. Preprocessing is being performed to correct for sensor artifacts and atmospheric effects.

Integration of the satellite data with ground-based measurements from monitoring stations has been done for validation and calibration purposes. Then, different maps showing concentration levels of different pollutants across various regions have been generated, and air quality data obtained from CAAQM station operated by CPCB and UPPCB is compared with WHO standard.

Questionnaire

The questionnaire used in this study aimed to assess residents'

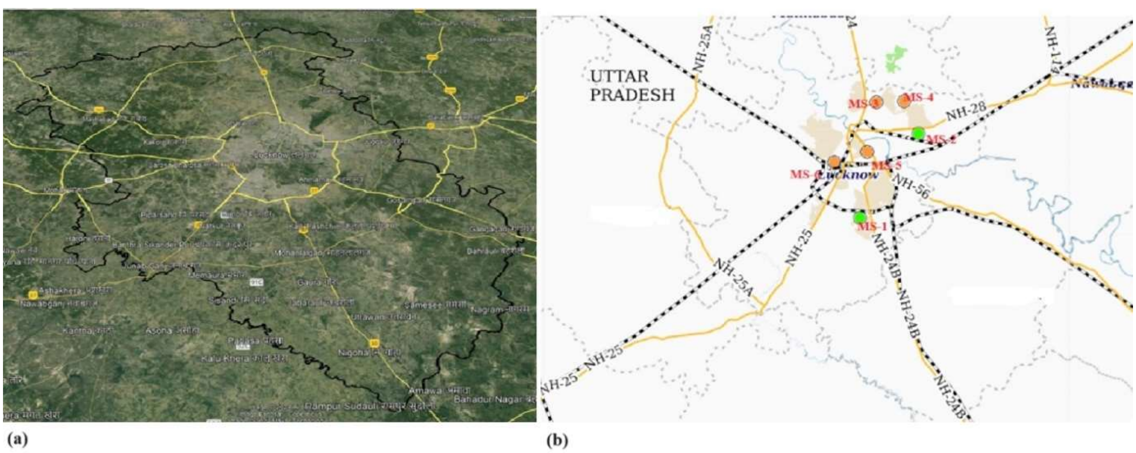

Fig. 1: Study area.

Table 3: Multiple spatial and temporal data types.

Platform/instrument	Sensor	Bands	Image format	Spatial resolution	Units	Extracted data
Sentinel-5P	Tropomi	7	HDF5	5.5 × 3.5 km	$MoL.m^{-2}$	NO_2, CO_2, PM_{10}

opinions on air pollution levels and their respiratory health status. Created with Google Forms and distributed via email to 200 residents, the questionnaire had two main sections. The first section focused on residents' demographics, their understanding and experiences regarding air quality, and their views on existing air pollution laws. The second section addressed their respiratory health conditions, awareness of pollution, and its impact on both the built environment and their health.

RESULTS AND DISCUSSION

Comparison of Key Air Pollutant Level (NO_2, SO_2) Obtained from Satellite Data with Ground Level Monitoring

Analysis of temporal trends in air pollution levels over one year from January 1 to December 31, 2023, has been made, observing fluctuations in pollutant concentrations across

Table 4: Four official seasons designated by the Indian Meteorological Department (IMD).

Colors Representation	Season
	Winter
	Summer or pre-monsoon
	Monsoon or rainy
	Post-monsoon

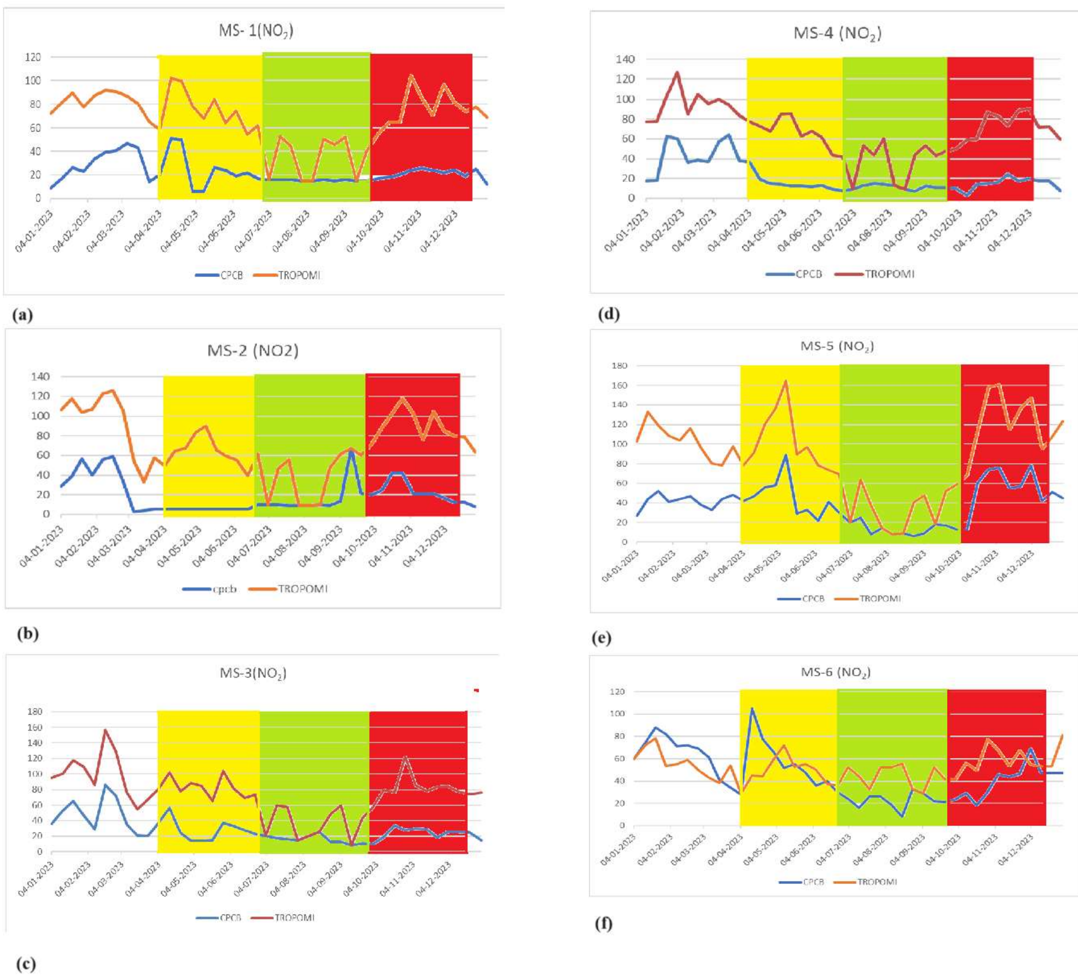

Fig. 2: Comparative prediction of monthly variation of NO_2 level in (a) MS 1,(b) MS 2,(c) MS 3,(d) MS 4,(e) MS 5 and (f) MS 6.

different seasons and involving the examination of ground-based air quality monitoring data to validate and integrate the observations obtained from satellites. The seasonal variations in the data were categorized based on color representation, as shown in Table 4. These categories include Winter, Summer or Pre-Monsoon, Monsoon or Rainy, and Post-Monsoon.

Fig. 2 presents the monthly variation in NO_2 levels and the examination of ground-based air quality monitoring data to validate and integrate the observations obtained from satellites in MS 1, MS 2, MS 3, MS 4, MS 5, and MS 6. Higher concentrations during winter months were observed due to increased emissions from heating sources and stagnant atmospheric conditions. During winter, temperature inversion phenomena are common, especially in urban areas like Lucknow. Inversions trap pollutants, including NO_2, close to the ground as colder air near the surface is denser and prevents vertical mixing. This leads to the accumulation of pollutants, resulting in higher NO_2 concentrations. Rainy months showed much lower concentrations due to rainfall acts as a natural cleanser by washing pollutants, including NO_2, out of the atmosphere. The precipitation effectively removes NO_2 molecules from the air, leading to reduced concentrations. During rainy weather, increased humidity levels and the presence of water vapor can facilitate chemical reactions that result in the transformation or removal of NO_2 from the atmosphere through processes like dissolution and oxidation. Enhanced atmospheric dispersion due to windy and turbulent conditions associated with rain can result in the dilution of pollutants, including NO_2, leading to lower concentrations in the air.

Fig. 3 presents the monthly variation in SO_2 levels in MS 1, MS 2, MS 3, MS 4, MS 5, and MS 6, showing higher concentrations during winter months due to increased emissions from combustion sources and stagnation of air

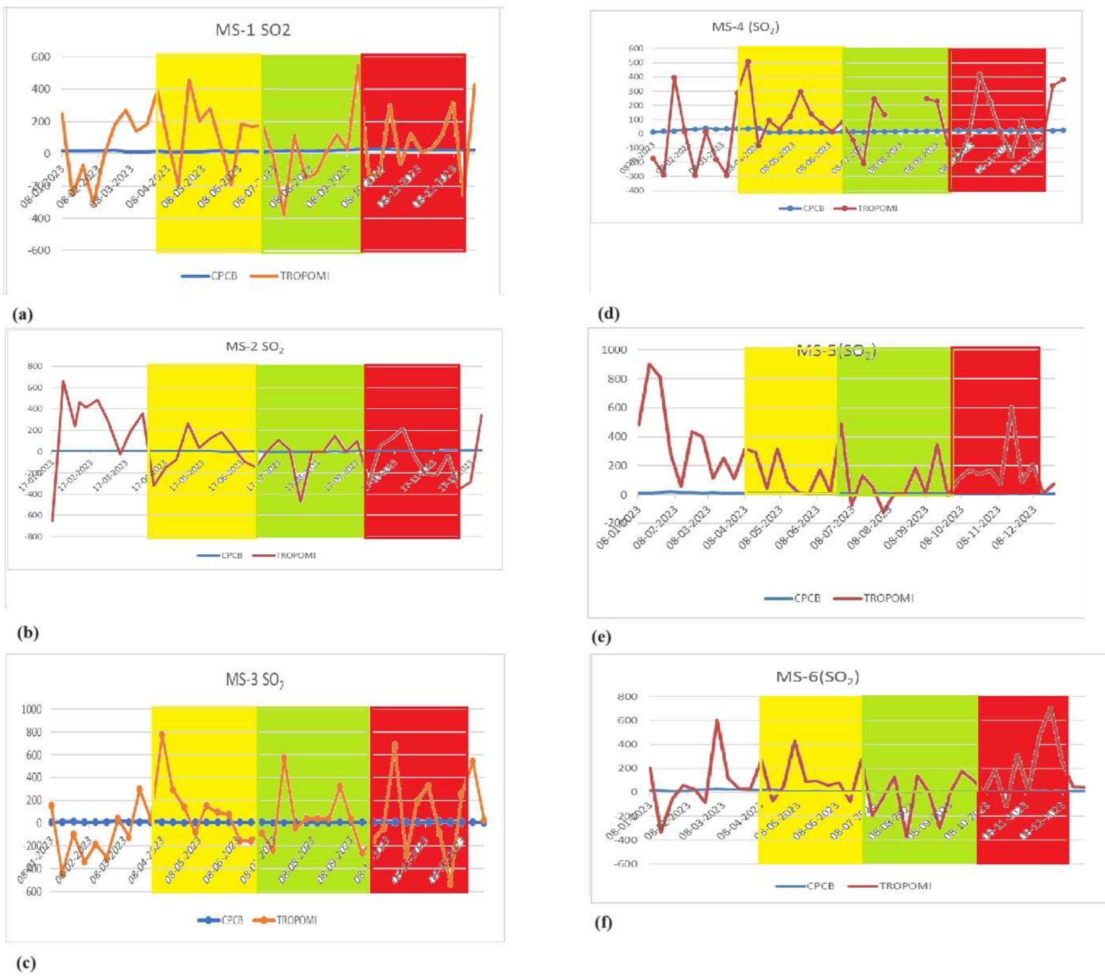

Fig. 3: Comparative prediction of monthly variation of SO_2 level in (a) MS 1,(b) MS 2,(c) MS 3,(d) MS 4,(e) MS 5 and (f) MS 6.

leading to the accumulation of pollutants like SO_2, especially in urban areas where emissions are high.

Comparison of Key Air Pollutant Levels (NO_2, SO_2, and PM_{10}) Obtained from CAAQM Stations of CPCB and UPPCB with WHO Standard

A comparison of measured pollutant concentrations with WHO standards has been done to assess compliance and identify areas of concern. Fig. 4(a) and 4(c) indicate that MS-1 of Lucknow city exceeds permissible limits for NO_2 in the winter season and PM_{10} in all seasons, highlighting the need for targeted interventions to mitigate air pollution and safeguard public health. This is mainly because, during winter, meteorological conditions such as temperature inversions can trap pollutants close to the ground, leading to higher concentrations of NO_2 and other pollutants. In colder months, there is typically an increase in the use of fossil fuels for heating purposes, particularly in residential areas. This can lead to higher emissions of NO_2 from sources such as residential heating systems and vehicles.

Winter months often experience stagnant air masses, which can result in the accumulation of pollutants, including NO_2, in the atmosphere. Cold weather can affect vehicle engines and reduce the efficiency of emission control systems, leading to higher emissions of NO_2 from vehicles.

The high PM_{10} concentration in the MS-1 of Lucknow city throughout the year could be attributed to several factors: MS-1 experiences heavy traffic congestion, especially during peak hours. Vehicle emissions, particularly from diesel engines, contribute significantly to PM10 levels due to the release of particles from exhaust fumes and brake wear. There are ongoing construction projects nearby, and activities such as excavation, demolition, and material transport can generate dust particles, contributing to PM10 level. There are large open spaces or bare soil areas nearby, and wind erosion can lift dust particles into the air, adding to the PM10 concentration. Fig. 4(b) shows the SO_2 level is below baseline. This is due to MS-1 having less industrial activity compared to other areas, leading to lower emissions of sulfur dioxide. Industries like power plants, refineries, and manufacturing facilities are major sources of SO_2 emissions.

Similarly, Fig. 5(a) and 5(c) show that MS-2 of Lucknow city exceeds permissible limits for NO_2 in the winter season and PM_{10} in all seasons, highlighting the need for targeted interventions to mitigate air pollution and safeguard public health. Fig. 5(b) indicates SO_2 level is below the baseline.

Similarly, Fig. 6(a) and 6(c) indicate that MS-3 of Lucknow city exceeds permissible limits for NO_2 in the winter season and PM_{10} in all seasons, highlighting the need for targeted interventions to mitigate air pollution and

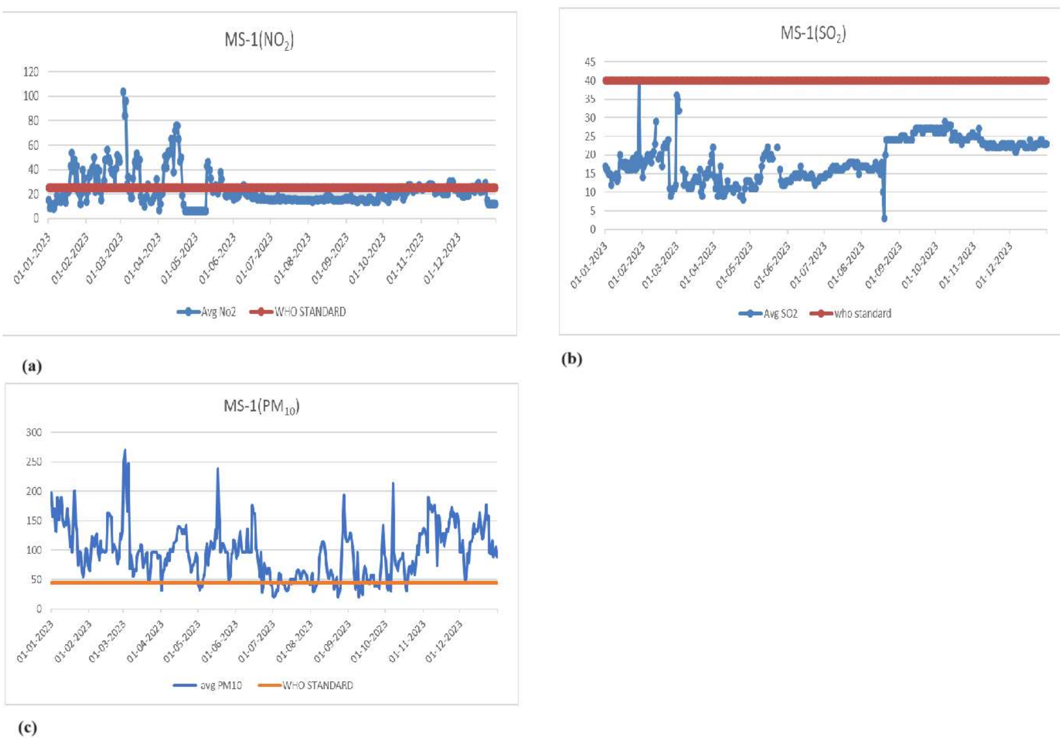

Fig. 4: Comparative prediction of ground truth (a)NO_2,(b) SO_2, and (c) PM_{10} with WHO standards of MS-1.

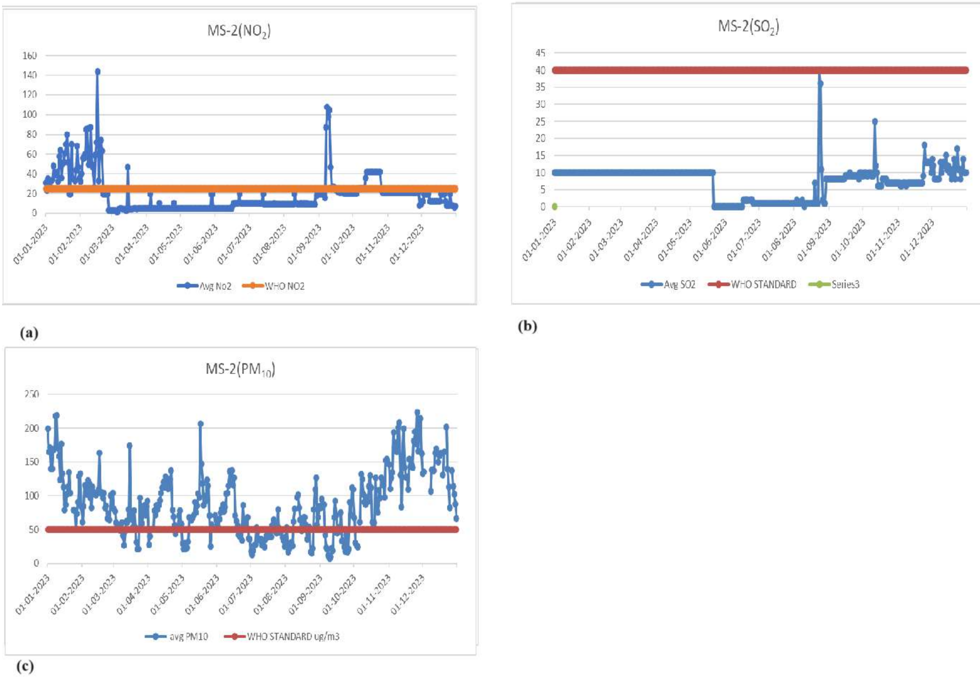

Fig. 5: Comparative prediction of ground truth (a)NO_2,(b) SO_2, and (c) PM_{10} with WHO standards of MS-2.

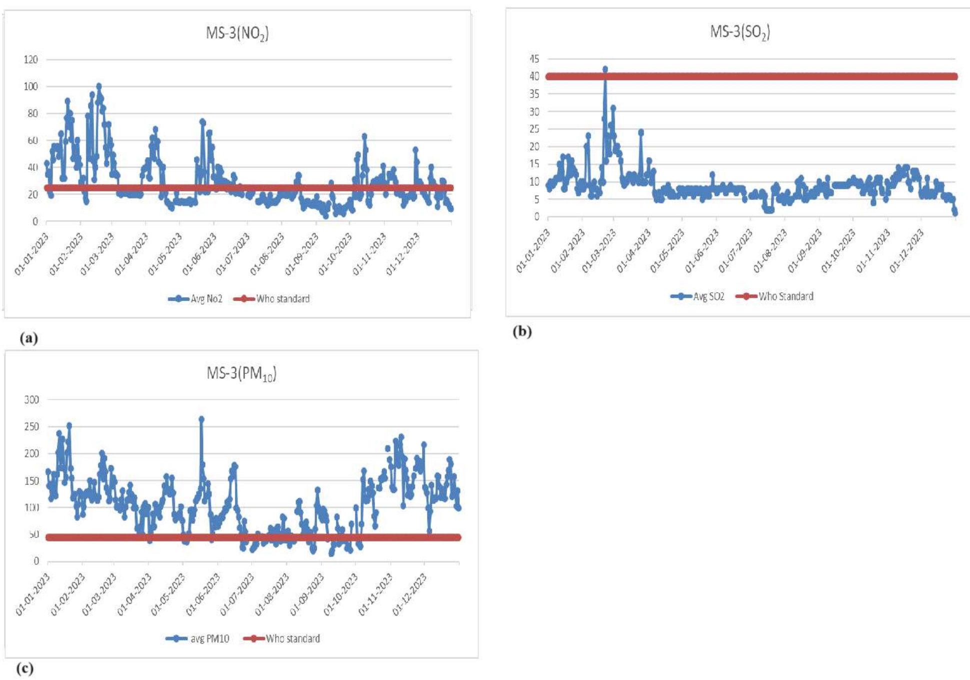

Fig. 6: Comparative prediction of ground truth (a)NO_2,(b) SO_2, and (c) PM_{10} with WHO standards of MS 3.

safeguard public health. Fig. 6(b) indicates SO_2 level is below the baseline.

Similarly, Fig. 7(a) and 7(c) indicate that MS-4 of Lucknow city exceeds permissible limits for NO_2 in the winter season and PM_{10} in all seasons, highlighting the need for targeted interventions to mitigate air pollution and safeguard public health. Fig. 7(b) indicates SO_2 level is below the baseline.

Fig. 7: Comparative prediction of ground truth (a)NO_2,(b) SO_2, and (c) PM_{10} with WHO standards of MS 4.

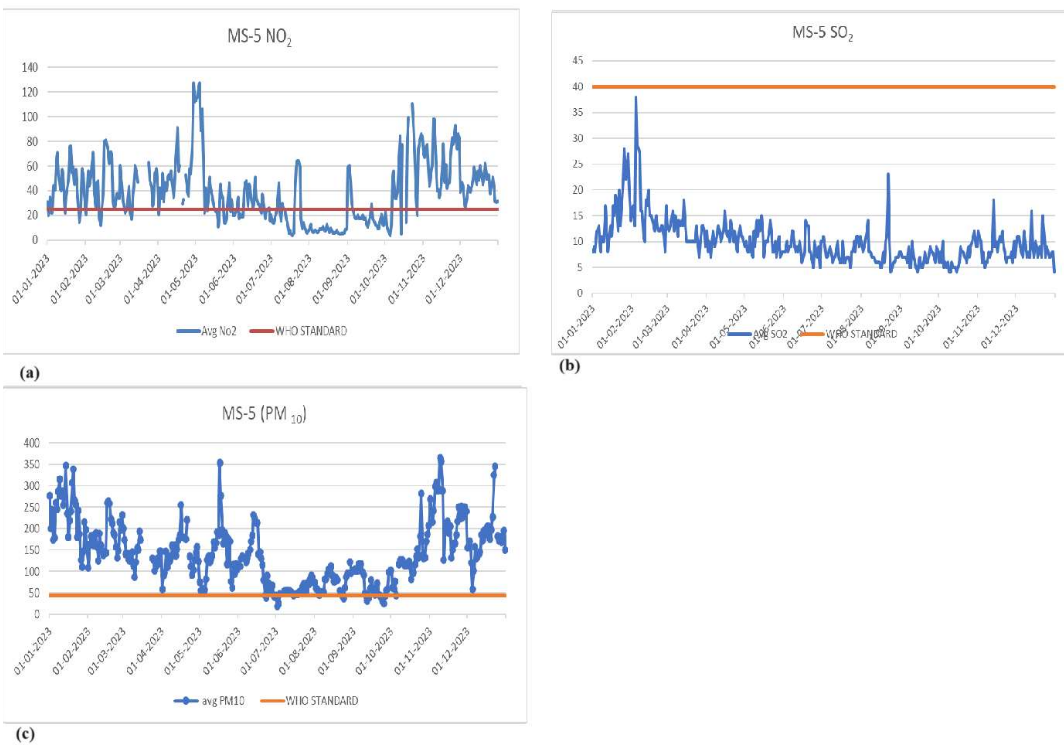

Fig. 8: Comparative prediction of ground truth (a)NO_2, (b) SO_2, and (c) PM_{10} with WHO standards of MS 5.

Similarly, Fig. 8(a) and 8(c) indicate that MS-5 of Lucknow city exceeds permissible limits for NO_2 and PM_{10} in all seasons, highlighting the need for targeted interventions to mitigate air pollution and safeguard public health. MS-5 is situated in a commercial area, so Commercial areas typically experience heavy traffic flow, leading to increased emissions of NO_2 from vehicles. NO_2 is a common pollutant produced by combustion engines, especially diesel vehicles, and traffic congestion can exacerbate its levels. It also hosts small-scale industrial activities, such as workshops or small factories, which can emit pollutants, including NO_2 and PM_{10}. These emissions are continuous throughout the year. Fig. 8(b) indicates SO_2 level is below the baseline.

Similarly, Fig. 9(a) and Fig. 9(c) indicate that MS-6 of Lucknow city exceeds permissible limits for NO_2 and PM_{10} in all seasons, highlighting the need for targeted interventions to mitigate air pollution and safeguard public health. MS-6 is situated in an industrial area. Industrial areas typically experience heavy traffic flow due to transportation of goods, employees commuting to work, and logistics operations. This can lead to increased emissions of NO_2 from vehicles, especially diesel-powered trucks and industrial vehicles. Many industries in MS-6 may rely on the combustion of fossil fuels such as coal, oil, and natural gas for energy generation and production processes. These combustion processes release NO_2 and PM_{10} as byproducts, contributing to air pollution in the area. MS-6 has fewer green spaces compared to residential or commercial areas. Greenery helps in absorbing pollutants and improving air quality. The absence of vegetation in MS-6 exacerbates air pollution by allowing pollutants to accumulate without being absorbed.

The spatial distribution of air pollutants in Lucknow city reflects the influence of both anthropogenic and natural factors, including industrial activities, vehicular emissions, and meteorological conditions. Hotspots of NO_2 and SO_2 concentrations coincide with industrial zones and major roadways, emphasizing the contribution of vehicular traffic and industrial emissions to local air quality degradation. The observed spatial patterns provide valuable insights for urban planners and policymakers to prioritize mitigation efforts and implement zoning regulations to reduce exposure to harmful pollutants.

The observed seasonal variability in air pollution levels underscores the influence of seasonal meteorological patterns and seasonal anthropogenic activities on air quality.

Winter months exhibit higher concentrations of pollutants such as NO_2 and PM_{10} due to increased emissions

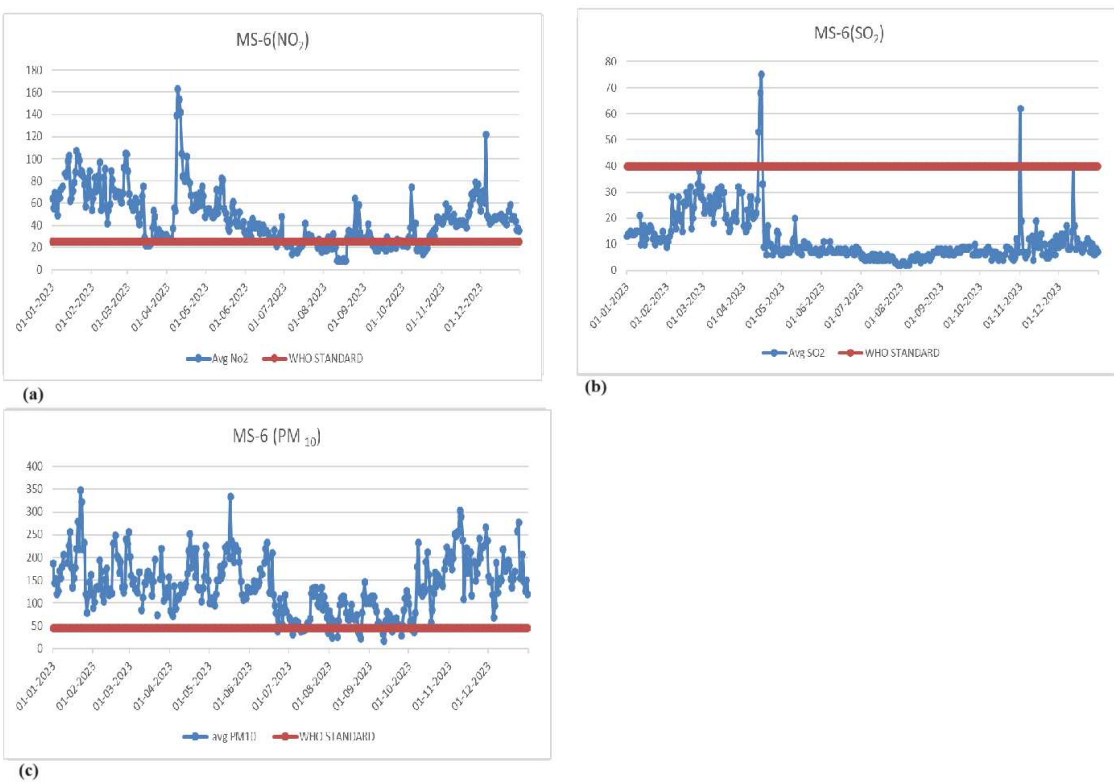

Fig. 9: Comparative prediction of ground truth (a) NO_2, (b) SO_2, and (c) PM_{10} with WHO standards of MS 6.

from heating sources, agricultural residue burning, and atmospheric stagnation. Understanding these seasonal trends is essential for implementing targeted interventions and seasonal pollution control measures to mitigate the adverse effects of air pollution on public health and the environment.

Our findings have significant implications for air quality management and policy development in Lucknow city, emphasizing the importance of implementing stringent emission controls and promoting sustainable urban development practices.

Future research efforts should focus on refining spatial modeling techniques, integrating additional data sources, and conducting longitudinal studies to monitor changes in air pollution levels and assess the effectiveness of pollution control measures over time.

Evaluating the Health Impacts of Air Pollution in Lucknow City

The analysis of the questionnaire yields significant insights into the demographics and perceptions regarding air pollution in the study area of Lucknow. Most respondents, approximately 53.2%, fall within the age group of 20-25 years. This indicates that younger individuals are actively engaged in the survey, reflecting a potential concern among the youth regarding air pollution. About 36.4% of the respondents are employed in the private sector, while 16.5% are from the government sector, and the remaining respondents are from other sectors (Fig. 10). This distribution suggests a diverse representation across various employment sectors.

All respondents were selected to be residents in the study area Fig. 34, ensuring that the survey accurately reflects the opinions and experiences of individuals directly affected by local air pollution issues.

The survey results confirm a correlation between air pollution and deteriorated respiratory health status, especially among sensitive groups and different age cohorts. This highlights the urgent need for interventions to address air quality issues, particularly for vulnerable populations. The survey identifies traffic and transportation, rapid urbanization, and population growth as the primary contributors to air pollution in Lucknow.

These findings underline the multifaceted nature of the problem, implicating both anthropogenic activities and urban development patterns. Despite acknowledging the presence of strong air pollution laws in the country (33.8%), a substantial portion of respondents (55.3%) also believe that air pollution is contributing to the extinction of flora and fauna. This suggests a perception of regulatory inadequacy or enforcement challenges in mitigating environmental degradation.

CONCLUSIONS

In conclusion, this research paper has provided a comprehensive analysis of key air pollutants, namely nitrogen dioxide (NO_2) and sulfur dioxide (SO_2), utilizing satellite remote sensing data from TROPOMI Explorer in Lucknow City. Through the utilization of advanced satellite technology, we were able to gather valuable insights into the spatial distribution and concentration levels of these pollutants across the city.

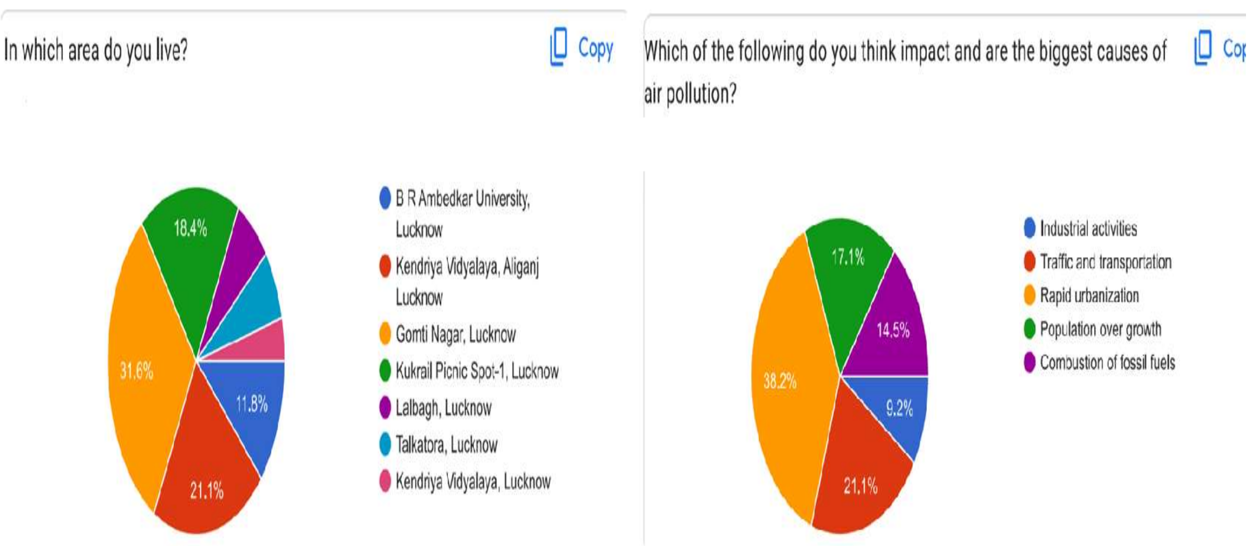

Fig. 10: Resident area.

The findings of this study shed light on the extent of air pollution in Lucknow City, highlighting areas of elevated pollutant levels and potential sources of emissions. This information is crucial for policymakers and stakeholders in formulating effective strategies to address air quality issues and protect public health.

Furthermore, the use of satellite remote sensing data has provided a cost-effective and efficient means of monitoring air quality on a large scale, complementing ground-based monitoring efforts. This integrated approach enhances our understanding of air pollution dynamics and facilitates informed decision-making towards mitigating its adverse impacts.

This research paper has successfully utilized Geographic Information Systems (GIS) and remote sensing techniques to map and analyze air pollution levels in Lucknow City. By integrating these advanced technologies, we have gained valuable insights into the spatial distribution and concentration of air pollutants within the urban environment.

Comparisons with WHO air quality standards have highlighted areas where pollution levels exceed recommended thresholds, emphasizing the urgent need for targeted interventions to improve air quality and safeguard public health in Lucknow City.

The application of GIS and remote sensing has proven to be a powerful tool in environmental monitoring, providing policymakers and stakeholders with actionable data for informed decision-making. This research underscores the importance of continued investment in technological innovations to address the complex challenges of urban air pollution and create healthier, more sustainable cities for future generations.

This research underscores the significance of leveraging satellite remote sensing technology for monitoring air quality and emphasizes the importance of continued efforts in addressing environmental challenges for the well-being of present and future generations.

Limitations and Future Scope

The Sentinel-5P TROPOMI sensor provides valuable data for air quality assessment, but it has some limitations. Its spatial resolution may not capture localized pollution variations within Lucknow, potentially missing critical hotspots. The temporal resolution is another limitation, as satellite data were collected only at specific times, which may not reflect daily variations in pollution levels. Cloud cover and adverse weather conditions can obscure satellite observations, leading to data gaps. Additionally, TROPOMI measures total column concentrations, lacking detailed vertical profiles that distinguish surface-level pollution from higher altitudes. Regular calibration with ground-based sensors is essential to ensure accuracy, and discrepancies may arise if calibration is not maintained. Furthermore, TROPOMI does not cover all pollutants, missing critical data on particulate matter and volatile organic compounds.

Future research should integrate satellite data with ground-based monitoring to improve accuracy and resolution. Advanced analytics, including machine learning, can enhance data processing and pattern recognition. High-resolution satellite sensors in future missions will provide more detailed data. Longitudinal studies using TROPOMI data can reveal long-term trends and policy impacts. Combining air quality data with health studies will elucidate the impact of pollution on public health. Public awareness initiatives and multi-sensor platforms can provide comprehensive air quality insights. Additionally, studying the interplay between air quality and climate change using TROPOMI data will be crucial for developing holistic environmental strategies.

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