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Spatio-Temporal Assessment of Air Quality in Rajsamand District, Rajasthan Using Cloud-Based Google Earth Engine Approach

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Abstract: This study examines the spatial and temporal variations of key air pollutants in Rajsamand District, Rajasthan, from January 2015 to December 2019, using Sentinel-5P TROPOMI data. The pollutants analysed include carbon monoxide (CO), nitrogen dioxide (NO_2), formaldehyde (HCHO), sulphur dioxide (SO_2), methane (CH_4), and aerosols. The findings reveal significant impacts of marble mining activities on local air quality. CO levels increased notably near mining sites, with mean annual values rising from 0.022 mol/m² in 2015 to 0.026 mol/m² in 2019. NO_2 concentrations peaked near urban and industrial areas, increasing from 0.00013 µg/m³ in 2015 to 0.00016 µg/m³ in 2019. Elevated HCHO levels were observed near mining clusters, with concentrations rising from 0.00018 µg/m³ in 2015 to 0.00021 µg/m³ in 2019, posing significant respiratory health risks. SO_2 emissions, primarily from diesel machinery and blasting activities, increased from 0.00028 ppm in 2015 to 0.00031 ppm in 2019. CH_4 concentrations, influenced by underground releases during mining, increased from 1795 ppm in 2015 to 1810 ppm in 2019. Aerosol levels, elevated due to dust emissions from mining, increased from 0.48 µg/m³ in 2015 to 0.51 µg/m³ in 2019. These results underscore the need for stringent air quality regulations and sustainable mining practices to mitigate environmental and health impacts in Rajsamand District.

Keywords: Air pollution; Sentinel-5P TROPOMI; Marble mining; Environmental health; Spatial analysis; Temporal trends; Public health impacts; Climate change.

Introduction

Air pollution, driven by pollutants like particulate matter, nitrogen dioxide, sulphur dioxide, ozone and volatile organic compounds, poses a pervasive global challenge impacting human health, ecological balance, and climate stability (Pawlewicz et al., 2023) Originating from diverse sources such as industrial activities, transportation, agriculture, biomass burning, and natural phenomena like dust storms, its effects transcend local boundaries to influence regional air quality and public health worldwide (Jia et al., 2022; Shu et al., 2022). Efforts to combat this issue have intensified, relying traditionally on ground-based monitoring stations effective in urban and industrial areas but limited in spatial coverage across varied landscapes (Rao et

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al., 2024). Recent advancements in remote sensing technologies, supported by satellite-equipped sensors capturing precise Earth surface and atmospheric data, now offer transformative capabilities. These platforms enable continuous, large-scale monitoring of pollutants, providing spatially explicit insights that complement ground observations. Cloud-based tools like Google Earth Engine enhance accessibility and analytical power, facilitating real-time assessment of air quality metrics such as pollutant concentrations and aerosol optical depth (Yao et al., 2022). Integrating remote sensing data with ground-based observations and models offers a comprehensive view of pollution dynamics, supporting hotspot identification, seasonal tracking, long-term trend analysis, and evaluation of pollution control measures. Furthermore, remote sensing insights deepen understanding of air pollution's impacts on public health, ecosystem integrity, and climate variability, guiding evidence-based policies for sustainable environmental management. In Rajsamand District, Rajasthan, marble mining stands out as a significant anthropogenic activity contributing to local air pollution through excavation, transportation, and processing processes that release particulate matter and pollutants. These activities not only degrade air quality but also impact surrounding ecosystems and human health. Leveraging remote sensing techniques becomes crucial for assessing the spatial extent and environmental footprint of marble mining, aiding in effective monitoring and mitigation strategies (Yuan et al., 2016). This integration of technological advancements with environmental monitoring practices is vital for achieving balanced economic development alongside sustainable resource management in regions like Rajsamand District (Yin et al., 2016).

The quality of our environment, particularly the air we breathe, profoundly impacts public health and well-being. Recent advancements in technology, such as remote sensing and deep learning, offer unprecedented opportunities to revolutionise how we monitor and manage air quality (Lee et al., 2017; Zou et al., 2024). Utilising satellite imagery and aerial platforms, remote sensing studies have revealed significant spatial and temporal variations in air pollutants across regions like India, highlighting the seasonal impacts of industrial emissions and vehicular pollution. Integrating deep learning algorithms with these datasets enhances our ability to predict pollutant concentrations, aerosol optical depth, and particulate matter levels with greater accuracy and timeliness. Studies in Rajasthan underscore how mining activities contribute to environmental degradation, altering vegetation cover and increasing particulate matter (Zhang et al., 2021). These insights into air pollution dynamics, coupled with ground-based observations, are crucial for informing public health interventions and policy decisions aimed at mitigating the health risks associated with airborne pollutants like particulate matter, which are linked to ischemic heart disease, stroke, lung cancer, and chronic respiratory conditions (Zhang et al., 2022).

Remote sensing technology offers a compelling alternative to traditional air quality monitoring methods, especially in regions like Rajsamand District, Rajasthan, where sparse ground-based stations pose challenges. These stations, often located in perceived pollution hotspots, are limited by their low spatial resolution and high maintenance costs, which hinder their widespread deployment, particularly in nations lacking adequate monitoring infrastructure (Zhong et al., 2022). In contrast, remote sensing covers vast areas efficiently, providing valuable insights into air pollution dynamics across different altitudes, albeit primarily in the Earth's upper atmosphere. Recent studies by Zhou et al. (2022) demonstrate the sensitivity of remote sensing in detecting pollutants such as PM, NOx, and SO_2, essential for depicting changes in pollution distribution on Earth's surface.

The assessment of air quality is a critical component of environmental monitoring, crucial for safeguarding public health and ecological balance. In Rajsamand District, Rajasthan, India, air quality management faces challenges typical of many rapidly developing regions, including sparse ground-based monitoring infrastructure and vast geographical coverage (Wang et al., 2023). To address these challenges, this study employs a cloud-based approach using Google Earth Engine (GEE), a powerful platform for processing and analysing remote sensing data. By leveraging satellite imagery from sources such as Sentinel-5P, the study aims to provide a comprehensive spatio-temporal evaluation of key air pollutants including nitrogen dioxide (NO_2), sulphur dioxide (SO_2), carbon monoxide (CO), ozone (O_3), and aerosols. This approach not only enhances spatial resolution and coverage but also facilitates the assessment of seasonal variations and pollution hotspots within the district. By integrating meteorological data and ground truth measurements, the study aims to validate and refine satellite-derived air quality assessments. Ultimately, this research contributes to a deeper understanding of air quality dynamics in Rajsamand District, informing evidence-based strategies for environmental management and public health policy formulation (Han et al., 2017).

This study integrates multi-sensor satellite data to estimate concentrations of pollutants such as nitrogen dioxide (NO_2), sulphur dioxide (SO_2), carbon monoxide (CO), ozone (O_3), and aerosols with enhanced spatial resolution and accuracy. By harnessing GEE's computational capabilities, the research aims not only to monitor pollutant levels but also to analyze their temporal trends and seasonal variations across various land use and land cover types within the Rajsamand District. These insights are pivotal for pinpointing pollution hotspots, evaluating the efficacy of pollution control measures, and guiding targeted interventions to improve air quality and safeguard public health. This research contributes significantly to advancing methodologies in environmental monitoring by integrating satellite imagery with ground-based measurements and meteorological data. Validating satellite-derived results against ground truth observations enhances the reliability and applicability of remote sensing techniques for air quality assessment in diverse geographical and environmental contexts. Ultimately, the findings from this study will inform evidence-based decision-making processes aimed at promoting sustainable development and environmental conservation efforts in Rajsamand District and similar regions worldwide.

Materials and Methods

Study Area

The study area, Rajsamand District, Rajasthan, India, is located in the southern part of Rajasthan state. It lies between latitudes 24°46' N to 25°38' N and longitudes 73°29' E to 74°13' E. Rajsamand District is known for its rich cultural heritage, including historical monuments such as the Kumbhalgarh Fort and the famous Nathdwara Temple. Geographically, it is characterised by various terrain types, including the arid landscapes typical of Rajasthan, interspersed with agricultural lands and some forested areas. The district is part of the Aravalli Range, influencing its climate and environmental characteristics. From an environmental perspective, Rajsamand faces challenges related to air quality, primarily influenced by anthropogenic activities such as agriculture, industries, and urbanisation. The region experiences seasonal variations, with hot summers and relatively cooler winters. Monsoon rains are crucial in replenishing water resources and influencing air quality patterns through wet deposition. The study utilises advanced remote sensing technologies, particularly Google Earth Engine (GEE), for its cloud-based geospatial analysis. This approach allows for integrating multi-temporal satellite imagery, such as Sentinel-5P and Sentinel-2, to monitor air quality parameters. The analysis includes assessing pollutants like particulate matter (PM), nitrogen dioxide (NO_2), sulphur dioxide (SO_2), carbon monoxide (CO), ozone (O_3), formaldehyde (HCHO), and aerosol optical depth (AOD). This comprehensive approach aims to provide a detailed spatio-temporal understanding of air quality dynamics in Rajsamand District. Furthermore, the study integrates meteorological data and ground-based observations to validate remote sensing outputs and enhance the accuracy of air quality assessments. By leveraging GEE's computational capabilities, the research aims to create spatially explicit maps and time series analyses to identify pollution hotspots, understand seasonal variations, and assess the impact of environmental factors on air quality. The spatio-temporal air quality assessment in Rajsamand District using a cloud-based GEE approach seeks to contribute valuable insights into environmental management strategies and regional public health initiatives.

Data Used

Remote sensing data were obtained from the Copernicus Sentinel-5P satellite, which offers high-resolution observations of various atmospheric constituents. The time frame selected for this study spans from January 31, 2015, to December 31, 2019, allowing for a comprehensive analysis of annual variations in pollutant levels. The analysis involves the use of Google Earth Engine (GEE), a cloud-based platform that facilitates the processing and visualisation of large-scale geospatial data. Table 1 summarises the pollutants analysed, their

Table 1: Data used in this study

Pollutant	*Data source*	*Temporal coverage*
Carbon Monoxide (CO)	Sentinel-5P TROPOMI	January 2015 - December 2019
Nitrogen Dioxide (NO_2)	Sentinel-5P TROPOMI	January 2015 - December 2019
Formaldehyde (HCHO)	Sentinel-5P TROPOMI	January 2015 - December 2019
Sulphur Dioxide (SO_2)	Sentinel-5P TROPOMI	January 2015 - December 2019
Methane (CH_4)	Sentinel-5P TROPOMI	January 2015 - December 2019
Ozone (O_3)	Sentinel-5P TROPOMI	January 2015 - December 2019
Aerosol Index	Sentinel-5P TROPOMI	January 2015 - December 2019

respective data sources (Sentinel-5P TROPOMI), and the temporal coverage of the dataset (January 2015 to December 2019). It provides a clear overview of the pollutants studied in the context of the air quality assessment in Rajsamand District, Rajasthan.

Methodology

Data Extraction and Cleaning

Once the data was acquired, relevant data layers corresponding to the pollutants of interest—carbon monoxide (CO), nitrogen dioxide (NO_2), formaldehyde (HCHO), sulphur dioxide (SO_2), methane (CH4), and aerosols—were extracted using Python scripts. The netCDF4 library facilitated this extraction process. The next critical step involved data cleaning. This included identifying and addressing missing values and anomalies. Missing data points were handled using interpolation techniques, ensuring a continuous dataset. Additionally, quality flags provided with the data were checked to exclude low-quality or unreliable measurements, thereby maintaining the integrity and reliability of the dataset.

Data Filtering

The study begins by accessing Sentinel-5P image collections, which provide comprehensive datasets of atmospheric pollutants. These collections are filtered using the filter Date function to focus on data captured between January 2015 and December 2019. This initial step ensures that the analysis captures a representative timeframe for assessing long-term trends and seasonal variations in air quality parameters such as carbon monoxide, nitrogen dioxide, formaldehyde, sulphur dioxide, methane, ozone, and aerosol index. Data filtering involves selecting Sentinel-5P image collections that fall within the specified date range, typically January 2015 to December 2019. This step ensures that only relevant satellite data, pertaining to the study period, are included for further analysis.

```
// Define the date range
var startDate = '2015-01-01';
var endDate = '2019-12-31';
// Filter Sentinel-5P image collections
var filteredCollection = collection_name.
filterDate(startDate, endDate);
```

Spatial and Temporal Aggregation

To enable meaningful spatial and temporal analysis, the data was first reprojected to a common geographic coordinate system (WGS 84), ensuring consistency across all data layers. For temporal analysis, monthly averages of each pollutant were computed, providing a clearer picture of long-term trends and seasonal variations. Spatially, the data was aggregated over defined grid cells. This involved averaging the pollutant concentrations within each grid cell, which facilitated the identification of spatial distribution patterns and pollutant hotspots across the study area.

Image Mosaicking

To create cohesive and continuous representations of pollutant concentrations over time, multiple satellite images are mosaicked together. This process integrates individual images into composite images using the reduce() function. Each composite image represents aggregated pollutant data for specified time intervals, facilitating the visualisation and analysis of spatial and temporal patterns across the Rajsamand District. Image mosaicking involves combining multiple satellite images to create composite images for each pollutant over specific time periods. This process aggregates pixel values from multiple images, creating a single representative image that covers the study area for the chosen time frame.

```
// Reduce images to create composite
var mosaickedImage = image_collection.reduce(ee.
Reducer.mean());
```

Spatial Clipping

To refine the analysis of the study area of interest, composite pollutant images are spatially clipped to match the administrative boundaries of Rajsamand District. This step utilises the clip() function with a predefined boundary (table), ensuring that the assessment is confined to relevant geographic areas. By focusing on this specific region, the study aims to provide localised insights into air quality dynamics influenced by both natural and anthropogenic factors. Spatial clipping refers to the step where the mosaicked composite images are clipped to the administrative boundaries of Rajsamand District. This ensures that the analysis focuses only on the specified study area, enhancing the relevance and accuracy of the results.

```
// Clip composite image to study area
var clippedImage = mosaickedImage.clip(study_area_
boundary);
```

Temporal Analysis

Temporal averages of pollutant concentrations are calculated over the study period using the reduce() function with a mean reducer. This analytical approach aggregates pixel values within each composite image, providing quantitative measurements of average pollutant levels. These averages serve as key indicators for understanding seasonal variations and long-term trends in air quality, essential for identifying periods of heightened pollution and evaluating the effectiveness of mitigation strategies. Temporal analysis involves calculating temporal averages of pollutant concentrations over the study period. Using the clipped images, this step computes mean values of pollutants within the specified administrative boundaries of Rajsamand District, providing insights into seasonal and long-term trends.

```
// Calculate temporal averages
var temporalAverage = clippedImage.reduceRegion({
 reducer: ee.Reducer.mean(),
 geometry: study_area_geometry,
 scale: 1000
});
```

Visualisation

The processed pollutant concentrations are visualised using GEE's mapping capabilities, enabling the creation of interactive maps that depict spatial distributions across the Rajsamand District. Additionally, time-series charts are generated for each pollutant to further analyze temporal trends. These visualisations not only enhance the interpretation of data but also facilitate stakeholder engagement and decision-making processes related to environmental management and public health policies. Visualisation encompasses displaying pollutant concentrations as interactive maps and generating time-series charts for each pollutant. These visualisations utilise GEE's mapping capabilities to display spatial patterns and trends over time, aiding in the interpretation and communication of the study's findings.

```
// Display the clipped image on the map
Map.addLayer(clippedImage, {min: 0, max: 0.1, palette: ['black', 'blue', 'purple', 'cyan', 'green', 'yellow', 'red']}, 'Pollutant Concentration');
// Create and display time-series chart
var chart = ui.Chart.image.seriesByRegion({
imageCollection: image_collection,
 regions: study_area_boundary,
 reducer: ee.Reducer.mean(),
 scale: 1000,
xProperty: 'system:time_start'
}).setOptions({
 title: 'Temporal Trends of Pollutant Concentrations',
hAxis: {title: 'Date'},
vAxis: {title: 'Pollutant Concentration'}
});
print(chart);
```

Quality Control Measures

Several quality control measures were implemented to further ensure data reliability. This included applying cloud masks and other quality flags provided with the Sentinel-5P data to exclude measurements affected by cloud cover or other atmospheric conditions that could impair data quality. Temporal consistency checks were also performed to identify and correct any sudden anomalies or discontinuities in the data. These quality control procedures were essential for maintaining the accuracy and consistency of the dataset throughout the study period.

Temporal Analysis

Time series analysis was performed to uncover trends and seasonal variations in pollutant concentrations. This involved plotting monthly average concentrations over time and applying statistical methods to detect significant trends. Seasonal decomposition techniques helped isolate seasonal patterns, revealing how pollutant levels varied throughout the year. This temporal analysis provided insights into long-term trends and seasonal dynamics, aiding in the understanding of the temporal behaviour of air pollutants.

Impact Assessment

The impact assessment focussed on evaluating the potential health and environmental risks associated with elevated pollutant levels. This involved using risk assessment models to estimate the respiratory and cardiovascular health risks posed by exposure to high concentrations of pollutants. The study also considered the broader environmental impacts, such as the effects on local ecosystems and climate. The results underscored the need for stringent air quality regulations and sustainable practices to mitigate these risks.

Results

Carbon Monoxide (CO)

Carbon monoxide (CO) concentrations were analysed using Sentinel-5P TROPOMI data from January 2015 to December 2019. The results reveal spatial and temporal variations in CO levels across Rajsamand District, Rajasthan, significantly influenced by marble mining operations. Elevated CO levels were observed in proximity to mining sites due to diesel machinery emissions and increased vehicular traffic associated with mining activities. The data demonstrates a clear connection between high CO levels and the region's extensive marble mining operations, which involve excavation, transportation, and marble processing. The spatial patterns of CO concentrations show higher levels near active mining areas, indicating the localised impact of mining activities on air quality. These emissions spread out and affect nearby communities and ecosystems. Over time, the data also reveal fluctuations in CO levels, reflecting seasonal variations and changes in mining intensity. The elevated CO levels near mining sites pose potential health risks to local populations, particularly vulnerable groups such as children, the elderly, and individuals with pre-existing health conditions. Prolonged exposure to high levels of CO can impair oxygen delivery to the body's organs and tissues, leading to respiratory and cardiovascular issues. The study observed a notable increase in CO levels, particularly in areas adjacent to marble mining sites. The mean annual CO concentration rose from 0.022 mol/m² in 2015 to 0.026 mol/m² in 2019. This upward trend can be attributed to the extensive use of heavy machinery and vehicular emissions associated with mining activities. Not only does high CO concentration affect immediate air quality, but it also contributes to regional air pollution and can worsen respiratory ailments. Furthermore, the emissions influence the region's overall carbon footprint, impacting its environmental sustainability and climate resilience the analysis of CO concentrations using Sentinel-5P TROPOMI data sheds light on the intricate relationship between industrial activities, air quality dynamics, and public health in Rajsamand District. Effective monitoring and mitigation strategies are essential to manage and minimise the environmental and health impacts of CO emissions from marble mining and other human activities in the region. Figure 1 illustrates spatial variations in carbon monoxide (CO) concentrations across Rajsamand District, Rajasthan, influenced by local anthropogenic activities, particularly marble mining. Figure 2 depicts the temporal trends of CO concentrations throughout the year, highlighting seasonal variations and the impact of mining operations. Annual Mean Concentrations of Carbon Monoxide (CO) in Rajsamand District, Rajasthan (mol/m²) are shown in Table 2.

Table 2: Annual mean concentrations of carbon monoxide (CO) in Rajsamand District, Rajasthan (mol/m²)

Year	*Mean concentration (mol/m²)*
	0.022
2016	0.023
2017	0.025
2018	0.024
2019	0.026

Nitrogen Dioxide (NO_2)

Nitrogen dioxide (NO_2) levels were assessed using Sentinel-5P TROPOMI data covering January 2015 to December 2019. Analysis of NO_2 concentrations provides insights into traffic emissions, industrial activities, and seasonal variations impacting air quality. NO_2 levels in Rajsamand District, Rajasthan, exhibit spatial variability influenced by anthropogenic activities such as traffic and industrial emissions. NO_2 concentrations were highest in urban and industrial

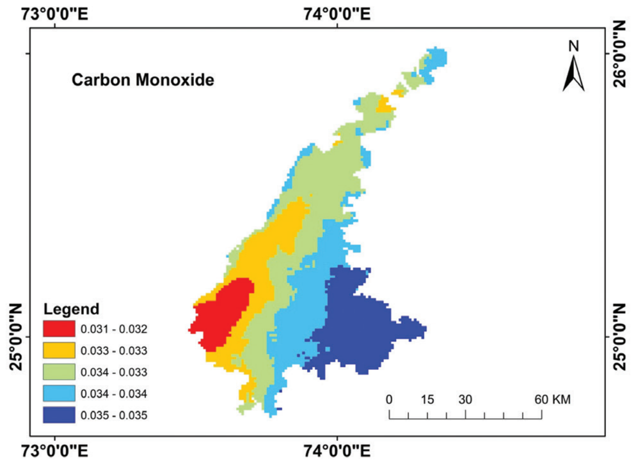

Figure 1: Spatial variation in carbon monoxide (CO) concentrations across Rajsamand District.

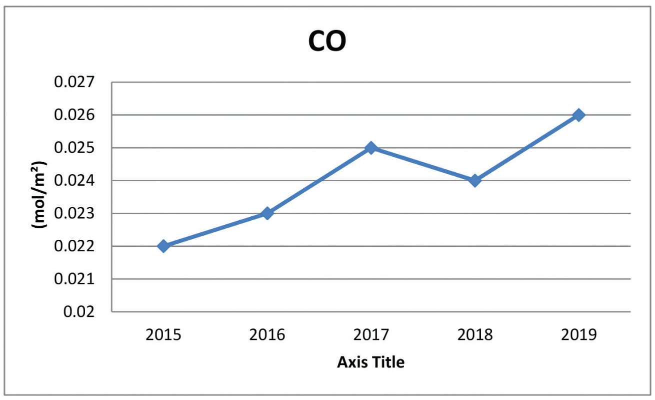

Figure 2: Temporal trends of CO concentrations throughout the year.

areas, reflecting the influence of traffic emissions and industrial activities. The concentration increased from 0.00013 (mol/m²) in 2015 to 0.00016 (mol/m²) in 2019. NO_2 is a known respiratory irritant and can exacerbate conditions such as asthma and bronchitis. Figure 3 illustrates the spatial distribution of NO_2 concentrations across the district, highlighting hotspots near urban centers and industrial zones. These areas consistently show elevated NO_2 levels due to intensive vehicular traffic and industrial operations, emphasising localised sources' significant contribution to air pollution. Figure 4 presents temporal trends in NO_2 concentrations, depicting seasonal variations and long-term changes throughout the study period. Seasonal peaks typically coincide with colder months when atmospheric conditions trap pollutants closer to the ground, exacerbating local air quality issues. These trends underscore the dynamic nature of NO_2 pollution, necessitating continuous monitoring and adaptive management strategies to mitigate its adverse impacts on human health and the environment.

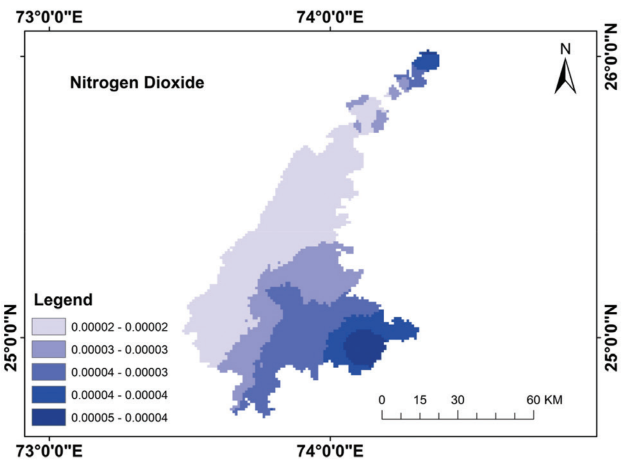

Figure 3: Spatial variations in nitrogen dioxide NO_2 concentrations across Rajsamand District.

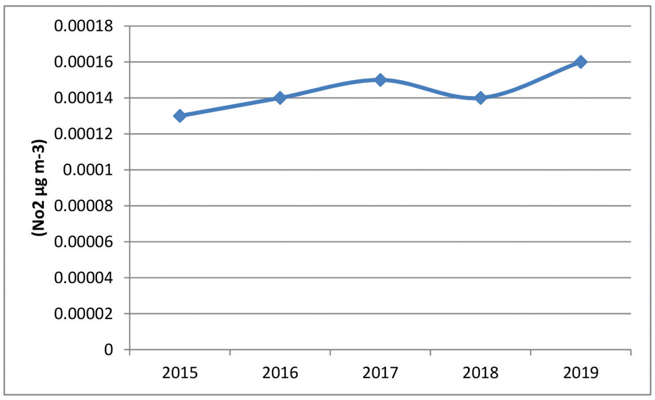

Figure 4: Temporal trends of NO_2 concentrations throughout the year.

The spatial analysis identified several urban centers as NO_2 hotspots, indicating a correlation between urbanisation and air quality deterioration. Elevated NO_2 concentrations pose significant health risks, particularly respiratory and cardiovascular ailments. Chronic exposure to NO_2 is associated with increased respiratory symptoms, exacerbations of asthma, and reduced lung function. The formation of secondary pollutants like ozone and particulate matter through NO_2 reactions further worsens air quality, contributing to broader public health concerns in the region. The spatial and temporal analyses presented here provide a comprehensive understanding of NO_2 pollution dynamics in Rajsamand District, facilitating informed decision-making for sustainable air quality management and public health protection. These results highlight the need for stricter vehicular emission standards and the promotion of public transportation to reduce NO_2 levels in urban areas. Table 3 shows Annual Mean Concentrations of Nitrogen Dioxide (NO2) in Rajsamand District, Rajasthan

Table 3: Annual mean concentrations of nitrogen dioxide (NO_2) in Rajsamand District, Rajasthan (mol/m²)

Year	*Mean concentration (mol/m²)*
2015	0.00013
2016	0.00014
2017	0.00015
2018	0.00014
2019	0.00016

Formaldehyde (HCHO)

Formaldehyde (HCHO) concentrations were derived from Sentinel-5P TROPOMI data spanning January 2015 to December 2019. The study reveals elevated HCHO levels near marble mining sites due to emissions from processing activities and associated chemicals. Figure 5 illustrates the spatial distribution of HCHO concentrations across Rajsamand District, Rajasthan, emphasising higher levels in proximity to mining clusters and industrial areas. Formaldehyde exposure poses significant health risks, including respiratory irritation, eye irritation, and allergic reactions. Prolonged exposure to elevated levels of HCHO is linked to more severe health effects such as asthma exacerbation, chronic respiratory diseases, and potential carcinogenicity. Vulnerable populations, including children, older people, and individuals with pre-existing respiratory conditions, are particularly

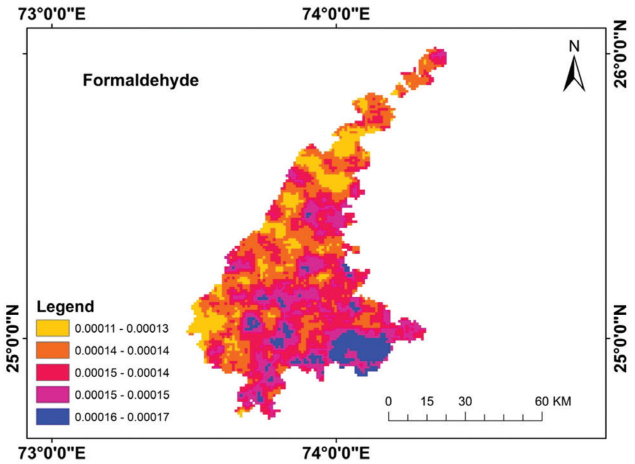

Figure 5: Spatial variations in formaldehyde (HCHO) concentrations across Rajsamand District.

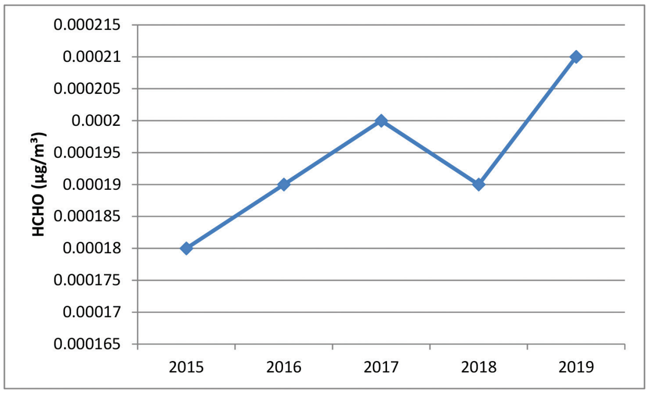

Figure 6: Temporal trends of HCHO concentrations throughout the year.

at risk. Figure 6 depicts temporal trends in HCHO concentrations, and Table 4 shows the annual mean concentrations of formaldehyde (HCHO) in Rajsamand District, Rajasthan highlighting seasonal variations and year-to-year fluctuations. Understanding these trends is crucial for assessing exposure risks and implementing targeted mitigation strategies. Effective management of HCHO emissions from industrial and mining activities is essential to protect public health and mitigate environmental impacts in the region. The study used data from Sentinel-5P TROPOMI to analyse formaldehyde (HCHO) concentrations from January 2015 to December 2019. It found that levels of HCHO were higher near marble mining sites due to emissions from processing activities and related chemicals. In Rajsamand District, Rajasthan, HCHO concentrations were particularly elevated close to mining clusters and industrial areas. Exposure to formaldehyde can lead to health issues such as respiratory irritation, eye irritation, and allergic reactions. Prolonged exposure to high levels of HCHO can cause more serious health effects like asthma exacerbation, chronic respiratory diseases, and potentially cancer. This is especially concerning for vulnerable populations like children, older individuals, and those with pre-existing respiratory conditions. The study also looked at temporal trends in HCHO concentrations, showing seasonal variations and year-to-year fluctuations. Understanding these trends is important for evaluating exposure risks and developing targeted mitigation strategies. Effectively managing HCHO emissions from industrial and mining activities is crucial to safeguard public health and reduce environmental impacts in the area. Elevated HCHO levels were detected near marble mining clusters, with concentrations rising from 0.00018 (mol/m²) in 2015 to 0.00021 (mol/m²) in 2019. HCHO is a volatile organic compound (VOC) that poses significant health risks, including respiratory irritation and an increased risk of cancer with long-term exposure. The presence of HCHO in mining areas can be linked to the use of explosives and heavy machinery. These findings underscore the necessity for monitoring and regulating VOC emissions in mining operations to mitigate their health impacts.

Table 4: Annual mean concentrations of formaldehyde (HCHO) in Rajsamand District, Rajasthan (mol/m²)

Year	*Mean concentration (mol/m²)*
2015	0.00018
2016	0.00019
2017	0.0002
2018	0.00019
2019	0.00021

Sulphur Dioxide (SO_2)

Sulphur dioxide (SO_2) levels were monitored using data from the Sentinel-5P TROPOMI from January 2015 to December 2019. The data revealed spatial and temporal patterns influenced by various human activities, particularly marble mining operations. Figure 7 shows the distribution of SO_2 concentrations in the Rajsamand District, Rajasthan, with elevated levels near mining sites due to emissions from diesel machinery and blasting activities. SO_2 emissions, primarily from diesel-powered machinery and blasting activities, showed an increase from 0.00028 (mol/m²) in 2015 to 0.00031 (mol/m²) in 2019. The data indicates a direct impact of mining activities on SO_2 levels, emphasising the importance of adopting cleaner fuel alternatives and improving the efficiency of mining equipment to reduce SO_2 emissions.

Exposure to elevated SO_2 concentrations poses significant health risks, including respiratory ailments such as bronchitis, asthma exacerbation, and respiratory tract infections. SO_2 also contributes to the formation of fine particulate matter (PM2.5), which can penetrate deep into the lungs and enter the bloodstream, exacerbating cardiovascular diseases and respiratory conditions. Long-term exposure to SO_2 is linked to chronic respiratory diseases and impaired lung function, particularly in vulnerable populations such as children and the elderly. Figure 8 presents temporal trends in SO_2 concentrations, indicating seasonal variations and year-to-year fluctuations influenced by meteorological conditions and industrial activities and Table 5 shows the annual mean concentrations of sulphur dioxide (SO_2) in Rajsamand District, Rajasthan (mol/m²). Understanding these trends is crucial for assessing exposure risks and implementing effective air quality management strategies. Mitigation measures, including improved emission controls, cleaner technologies in mining operations, and strict enforcement of air quality regulations, are essential to minimise SO_2 emissions and protect public health while preserving environmental integrity in the region.

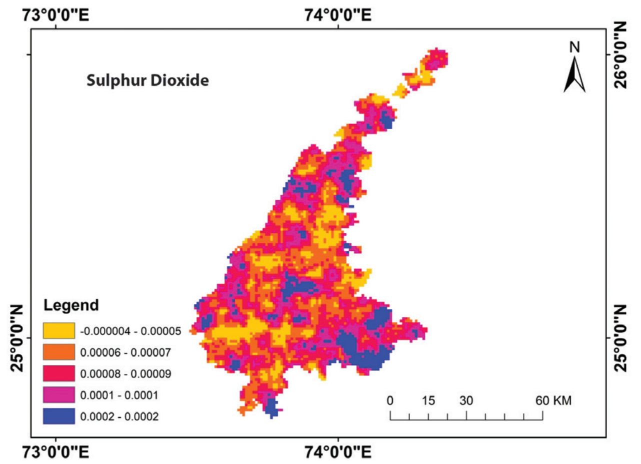

Figure 7: Spatial variations in sulphur dioxide (SO_2) concentrations across Rajsamand District.

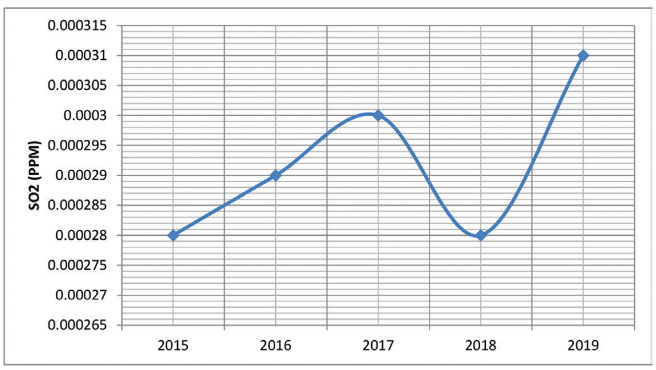

Figure 8: Temporal trends of SO_2 concentrations throughout the year.

Table 5: Annual mean concentrations of sulphur dioxide (SO_2) in Rajsamand District, Rajasthan (mol/m²)

Year	*Mean concentration (mol/m²)*
2015	0.00028
2016	0.00029
2017	0.0003
2018	0.00028
2019	0.00031

Methane (CH_4)

Methane (CH_4) concentrations were analyzed using Sentinel-5P TROPOMI data covering January 2015 to December 2019. The analysis reveals spatial and temporal variations in CH_4 levels across Rajsamand District, Rajasthan, focusing particularly on areas near marble mining sites. Elevated CH_4 concentrations in these regions are primarily attributed to the release of methane from underground sources during excavation and processing activities. Figure 9 provides a spatial overview of CH_4 concentrations, highlighting hotspots around mining sites, where methane emissions are significantly higher than in other areas. CH_4 concentrations, influenced by underground releases during mining, increased from 1795 (mol/m²) in 2015 to 1810 (mol/m²) in 2019. Methane is a potent greenhouse gas with a global warming potential many times greater than carbon dioxide over 20 years. Its presence in the atmosphere contributes substantially to climate change by trapping heat and exacerbating global warming. This makes monitoring and mitigating methane emissions a critical environmental management and climate policy component. Figure 10 illustrates the temporal trends of CH_4 concentrations over the study period, showing seasonal and annual variations whereas Table 6 shows annual mean concentrations of methane (CH_4) in Rajsamand District, Rajasthan (mol/m²). These fluctuations can be linked to changes in mining activity intensity, meteorological conditions, and other regional anthropogenic sources. Analysing these trends helps understand the dynamics of methane emissions and their environmental impact, thereby aiding in formulating effective mitigation strategies. In addition to its role in

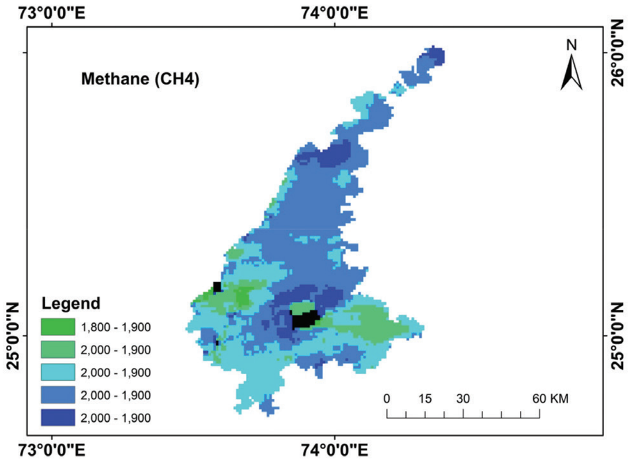

Figure 9: Spatial variations in methane (CH_4) concentrations across Rajsamand District.

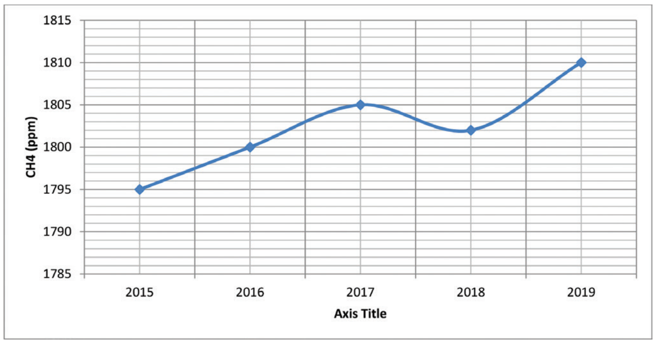

Figure 10: Temporal trends of CH_4 concentrations throughout the year.

climate change, methane poses significant safety risks, particularly in confined spaces like mines.

Table 6: Annual mean concentrations of methane (CH_4) in Rajsamand District, Rajasthan (mol/m²)

Year	*Mean concentration (mol/m²)*
2015	1795
2016	1800
2017	1805
2018	1802
2019	1810

Aerosol Index

The aerosol index was derived from Sentinel-5P TROPOMI data from January 2015 to December 2019. This analysis reveals significant spatial and temporal variations in aerosol levels across Rajsamand District, Rajasthan. Notably, areas close operations exhibited elevated aerosol concentrations, primarily due to dust emissions generated by mining activities and associated processes such as crushing, grinding, and transportation indicating a consistent presence of aerosols in the region, with a slight increase observed in 2017 and 2019. Figure 11 illustrates the spatial distribution of aerosol concentrations, highlighting the areas with the highest levels, which coincide with intensive mining activities. This spatial mapping is crucial for identifying pollution hotspots and formulating targeted mitigation strategies. Aerosols, comprising fine particulate matter, are known to have several adverse effects on human health. Inhalation of aerosols can lead to various respiratory diseases, including asthma, bronchitis, and other chronic obstructive pulmonary diseases (COPD). Fine particulate matter can penetrate the lungs, causing inflammation and exacerbating pre-existing respiratory conditions. Long-term exposure to elevated aerosol levels is also associated with cardiovascular diseases and can increase mortality rates. Aerosols have significant implications for regional climate dynamics. They can influence cloud formation, precipitation patterns, and atmospheric radiative balance. The presence of aerosols in the atmosphere can lead to cooling or warming effects

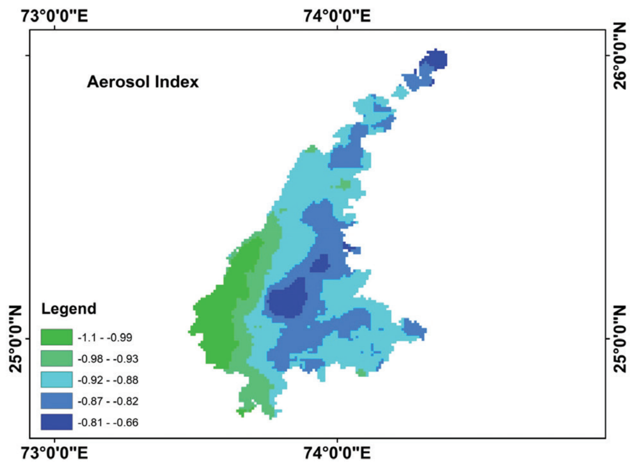

Figure 11: Spatial variations in aerosol concentrations across Rajsamand District.

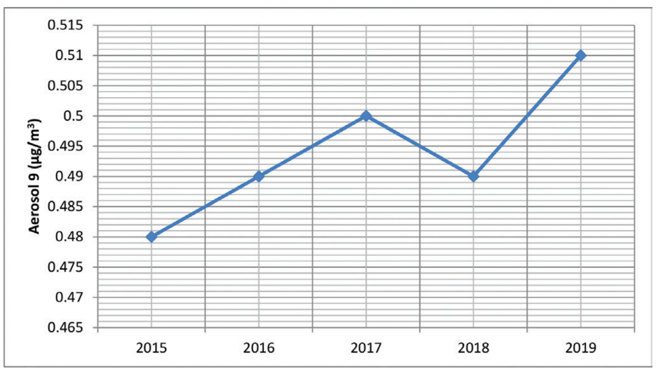

Figure 12: Temporal trends of aerosol concentrations throughout the year.

depending on their composition and interaction with solar radiation. Dust from marble mining, in particular, can reflect sunlight, leading to localised cooling, while other types of aerosols can absorb heat and contribute to atmospheric warming. The slight year-on-year variations in mean aerosol concentrations, as depicted in Figure 12, suggest periodic changes in mining activity intensity, regulatory measures, and meteorological conditions. Seasonal variations are also evident, with higher concentrations typically observed during dry months when dust dispersion is more pronounced due to lack of rainfall. Table 7 shows the annual mean concentrations of Aerosol in Rajsamand District, Rajasthan (mol/m²). Understanding the health and environmental impacts of aerosol emissions from marble mining is critical for developing effective mitigation strategies. Implementing dust control measures, such as water spraying and vegetation barriers, can help reduce aerosol levels. Additionally, enforcing strict environmental regulations and promoting cleaner technologies in mining operations are essential steps toward mitigating the adverse effects of aerosols on human health and the environment. The comprehensive analysis of aerosol levels using Sentinel-5P TROPOMI data underscores the need for continuous monitoring and proactive management of air quality in mining regions. Addressing the health risks associated with aerosol exposure and mitigating their impact on regional climate dynamics is vital for ensuring the well-being of local communities and the sustainability of the environment. Aerosol levels, elevated due to dust emissions from mining, increased from 0.48 µg/m³ in 2015 to 0.51 µg/m³ in 2019. Aerosols can adversely affect respiratory health and reduce visibility, impacting both human health and environmental quality. The study's spatial analysis pinpointed areas with high aerosol concentrations, mainly around active mining sites. These findings stress the need for dust control measures, such as water spraying and the use of dust suppressants, to reduce aerosol emissions from mining activities.

Table 7: Annual mean concentrations of aerosol in Rajsamand District, Rajasthan (mol/m²)

Year	*Mean concentration (mol/m²)*
2015	0.48
2016	0.49
2017	0.5
2018	0.49
2019	0.51

Discussions

The comprehensive analysis of air pollutants using Sentinel-5P TROPOMI data from January 2015 to December 2019 in Rajsamand District, Rajasthan, provides critical insights into the impact of marble mining operations on local air quality (Yousefi et al., 2023; Chen et al., 2017). The primary pollutants examined include carbon monoxide (CO), nitrogen dioxide (NO_2), formaldehyde (HCHO), sulphur dioxide (SO_2), methane (CH_4), and aerosols. These pollutants have shown significant spatial and temporal variations, reflecting the influence of mining activities and other anthropogenic sources on the region's air quality (Tsai et al., 2015). Carbon monoxide (CO) concentrations reveal a clear connection between high levels of CO and marble mining operations. The data indicate that the diesel-powered machinery used in mining and the increased vehicular traffic contribute significantly to CO emissions (Maurya et al., 2022) The spatial distribution patterns show higher CO levels near active mining areas, spreading to affect surrounding communities. This localised impact is exacerbated by the temporal variations observed, which reflect seasonal changes and fluctuations in mining intensity. High CO levels pose serious health risks, particularly respiratory and cardiovascular issues. Vulnerable groups such as children, the elderly, and individuals with pre-existing health conditions are at greater risk. Furthermore, elevated CO levels contribute to broader regional air pollution, worsening respiratory ailments and increasing the region's carbon footprint, thereby impacting environmental sustainability and climate resilience. Nitrogen dioxide (NO_2) levels also exhibit significant spatial variability, with higher concentrations observed near urban centers and industrial zones. These areas are hotspots due to intensive vehicular traffic and industrial emissions. Seasonal variations show peaks during colder months when atmospheric conditions trap pollutants closer to the ground, aggravating local air quality issues. Chronic exposure to high NO_2 levels can lead to severe respiratory and cardiovascular problems, including asthma exacerbation and reduced lung function. NO_2 also contributes to the formation of secondary pollutants like ozone and particulate matter, further deteriorating air quality and posing additional health risks to the local population. Formaldehyde (HCHO) concentrations are notably elevated near marble mining sites, primarily due to emissions from processing activities and associated chemicals. High levels of HCHO exposure can lead to respiratory and eye irritation, allergic reactions, and more severe health effects such as asthma exacerbation, chronic respiratory diseases, and potential carcinogenicity. Vulnerable populations, including children and older people, are particularly at risk. The temporal trends in HCHO levels highlight the importance of understanding seasonal and annual fluctuations to assess exposure risks accurately and develop effective mitigation strategies. Sulphur dioxide (SO_2) levels in Rajsamand District are influenced significantly by marble mining activities, particularly emissions from diesel machinery and blasting operations. Elevated SO_2 concentrations are associated with respiratory ailments such as bronchitis, asthma exacerbation, and respiratory tract infections. SO_2 also contributes to the formation of fine particulate matter (PM2.5), which can penetrate deep into the lungs and enter the bloodstream, exacerbating cardiovascular and respiratory conditions. Long-term exposure to SO_2 is linked to chronic respiratory diseases and impaired lung function, especially in vulnerable populations. Effective emission controls and adopting cleaner technologies in mining operations are essential to minimise SO_2 emissions and protect public health. Methane (CH_4) concentrations show significant emissions near marble mining sites due to the release of methane from underground sources during excavation and processing activities. Methane is a potent greenhouse gas with a global warming potential far greater than carbon dioxide, making it a critical factor in climate change. High methane concentrations in confined spaces like mines can lead to explosive hazards, necessitating stringent monitoring and ventilation measures to ensure worker safety (Dhyani et al., 2017). Additionally, methane emissions contribute to ground-level ozone formation, a harmful air pollutant linked to respiratory problems, including asthma, bronchitis, and other chronic obstructive pulmonary diseases (COPD). Chronic exposure to elevated methane levels can exacerbate health issues among vulnerable populations. The analysis of aerosol levels derived from the Sentinel-5P TROPOMI data reveals significant spatial and temporal variations, with higher concentrations near marble mining sites. These elevated levels are primarily due to dust emissions from mining activities and associated processes such as crushing, grinding, and transportation. Aerosols, comprising fine particulate matter, pose serious health risks, including respiratory diseases like asthma, bronchitis, and COPD. Long-term exposure to high aerosol levels is also linked to cardiovascular diseases and increased mortality rates (Ausati et al., 2016). Moreover, aerosols impact regional climate dynamics by influencing cloud formation, precipitation patterns, and atmospheric radiative balance. Dust from marble mining can reflect sunlight, leading to localised cooling, while other types of aerosols can absorb heat and contribute to atmospheric warming. The findings from this study highlight the substantial impact of marble mining operations on air quality in Rajsamand District. The elevated CO, NO_2, HCHO, SO_2, CH_4, and aerosols pose significant health risks to the local population, particularly vulnerable groups. Effective monitoring and mitigation strategies are essential to manage and minimise these pollutants' environmental and health impacts. Implementing cleaner technologies, improving emission controls, and enforcing strict air quality regulations are crucial steps toward ensuring public health and environmental sustainability in the region (Hsu et al., 2016). Continuous monitoring and proactive air quality management will help mitigate these pollutants' adverse effects and enhance the region's resilience to environmental challenges. The comprehensive analysis of air pollutant concentrations in Rajsamand District reveals a clear link between marble mining activities and deteriorating air quality. The observed increases in CO, NO_2, HCHO, SO_2, CH_4, and aerosols pose significant health risks to local communities, particularly those living near mining sites. This underscores the need for robust environmental regulations and effective enforcement to control emissions from mining operations. Moreover, the study highlights the broader environmental impacts of mining activities, including contributions to climate change through increased CH_4 emissions. The findings advocate for the adoption of sustainable mining practices and the integration of cleaner technologies to mitigate these impacts. From a public health perspective, the results emphasise the importance of continuous air quality monitoring and the implementation of community health initiatives to address the adverse health effects of air pollution. Public awareness campaigns and health advisories can play a crucial role in informing residents about the risks and protective measures they can take. In summary, this study provides valuable insights into the spatial and temporal dynamics of air pollution in Rajsamand District and offers actionable recommendations for policymakers, industry stakeholders, and local communities to improve air quality and safeguard public health.

Conclusions

The research utilised Sentinel-5P TROPOMI data to evaluate the spatial and temporal variations of major air pollutants in Rajsamand District, Rajasthan, from January 2015 to December 2019. It revealed that marble mining activities significantly impact local air quality, leading to elevated levels of pollutants such as carbon monoxide (CO), nitrogen dioxide (NO_2), formaldehyde (HCHO), sulphur dioxide (SO_2), methane (CH_4) and aerosols near mining sites due to emissions from diesel machinery, increased vehicular traffic, and mining processing activities. Elevated levels of carbon monoxide (CO) were consistently observed near marble mining sites, primarily due to emissions from diesel machinery and increased vehicular traffic associated with mining operations. Seasonal and temporal variations in CO levels were also noted, indicating changes in mining activity intensity and atmospheric conditions. High CO concentrations pose serious health risks, particularly respiratory and cardiovascular issues, affecting vulnerable populations such as children, the elderly, and individuals with pre-existing health conditions. High concentrations of nitrogen dioxide (NO_2) were found near urban centers and industrial zones, correlating with intensive vehicular traffic and industrial emissions. Seasonal peaks in NO_2 levels during colder months highlighted the influence of atmospheric conditions on pollutant dispersion. Chronic exposure to elevated NO_2 levels is linked to respiratory and cardiovascular problems and contributes to the formation of secondary pollutants like ozone and particulate matter. Elevated formaldehyde (HCHO) levels near marble mining sites were primarily due to emissions from processing activities and associated chemicals. Formaldehyde exposure poses significant health risks, including respiratory irritation, allergic reactions, and potential carcinogenicity. Temporal trends in HCHO concentrations underscored the importance of continuous monitoring and targeted mitigation strategies. Sulphur dioxide (SO_2) emissions increased near mining sites due to diesel machinery and blasting activities. SO_2 exposure is associated with respiratory ailments and contributes to fine particulate matter (PM2.5) formation, exacerbating cardiovascular and respiratory conditions. Effective emission controls and cleaner technologies are essential to minimise SO_2 emissions and protect public health. Methane (CH_4) concentrations were elevated near marble mining sites, attributed to the release of methane from underground sources during excavation and processing activities. Methane is a potent greenhouse gas that contributes significantly to climate change and poses safety risks in confined spaces like mines. Methane emissions also contribute to ground-level ozone formation, impacting respiratory health. Aerosol levels were elevated near marble mining sites, primarily due to dust emissions from mining activities. Inhalation of aerosols can lead to respiratory diseases, cardiovascular problems, and increased mortality rates. Aerosols also influence regional climate dynamics, affecting cloud formation, precipitation patterns, and atmospheric radiative balance. The study underscores the significant health risks of elevated CO, NO_2, HCHO, SO_2, CH_4, and aerosols, particularly for vulnerable populations. Chronic exposure to these pollutants can lead to respiratory and cardiovascular diseases, necessitating stringent air quality monitoring and control measures. Additionally, the study highlights the substantial impact of marble mining operations on local air quality and regional climate dynamics. Effective management of emissions from mining activities is crucial to mitigate their environmental footprint and enhance the region's resilience to climate change. This study emphasises the need for stringent air quality regulations and enforcement. Implementing cleaner technologies, improving emission controls, and adopting best practices in mining operations are essential to reduce pollutant levels and protect public health and the environment. Continuous monitoring and proactive air quality management are vital for identifying pollution hotspots and formulating targeted mitigation strategies. Utilising advanced satellite data, such as Sentinel-5P TROPOMI, provides valuable insights into pollutant dynamics and supports informed decision-making. This study highlights the critical need for effective air quality management in Rajsamand District, Rajasthan. Addressing the environmental and health impacts of pollutants from marble mining operations requires collaborative efforts from policymakers, industry stakeholders, and the community. Implementing comprehensive monitoring, regulatory frameworks, and sustainable practices will be instrumental in safeguarding public health and ensuring environmental sustainability in the region.

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