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RESEARCH ARTICLE

Seasonal Dynamics and Temporal Trends of SO_2 Pollution in Tamil Nadu (2024–2025) through Remote Sensing and Geographic Information System

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ABSTRACT

This study investigates the spatial and temporal distribution of sulphur dioxide (SO_2) pollution across Tamil Nadu, India, utilizing Sentinel-5P satellite data accessed through Google Earth Engine. Covering the year of 2024 and the initial two months of 2025, the research categorizes SO_2 concentrations into distinct seasonal periods: Summer (March–May), Monsoon (June–October), and Winter (November–February), offering insights into spatial and temporal variations in atmospheric SO_2 concentrations, the study aims to generate seasonal SO_2 pollution maps to highlight regional hotspots and variations. Furthermore, a time-series analysis will be conducted for the entire 2024-2025 period to identify overarching trends and significant pollution events. The findings revealed high SO_2 concentrations in northeastern Tamil Nadu. Seasonal analysis showed reduced levels during the monsoon due to rainfall cleansing, with a moderate resurgence in winter.

Keywords: *Sulphur Dioxide (SO_2),Air pollution, Sentinel-5P, Google Earth Engine, Quantum Geographic Information System, Tamil Nadu, India, Seasonal variations, Time Series Analysis.*

INTRODUCTION

Atmospheric sulphur dioxide (SO_2) is a major air pollutant with significant environmental and health implications. Primarily originating from the combustion of fossil fuels in industrial activities, power generation, and volcanic eruptions, SO_2 contributes to the formation of acid rain, fine particulate matter, and respiratory ailments (*Smith et al., 2011*; *WHO, 2006*). In rapidly developing regions like Tamil Nadu, India, industrial growth and increased energy demand often lead to elevated levels of atmospheric pollutants, necessitating continuous monitoring and assessment. Understanding the spatial and temporal patterns of SO_2 concentrations is crucial for effective environmental management, policy formulation, and public health protection.

Traditional ground-based monitoring networks, while accurate, often suffer from limited spatial coverage, particularly in vast and diverse geographical areas. Satellite-based remote sensing provides a robust and comprehensive alternative for monitoring large-scale atmospheric pollutants. The Copernicus Sentinel-5P mission, equipped with the TROPOspheric Monitoring Instrument (TROPOMI), provides high-resolution data on a range of atmospheric constituents,

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including SO_2, thereby enabling detailed investigations into air quality dynamics at regional scales (Veefkind et al., 2012).

This study leverages the capabilities of Sentinel-5P data, processed through the Google Earth Engine (GEE) cloud-based platform, to analyze SO_2 pollution patterns across the state of Tamil Nadu. By examining seasonal variations (Summer, Monsoon, Winter) and conducting a comprehensive time-series analysis for 2024 and early 2025, this research aims to identify areas with persistently high SO_2 levels, understand the influence of seasonal variation on pollutant dispersion, and provide an updated assessment of SO_2 air quality in the region. The generated pollution maps and time-series charts will serve as valuable resources for environmental agencies and policymakers in addressing air pollution challenges in Tamil Nadu.

MATERIALS AND METHODS

Study Area

The study area for this research is Tamil Nadu, a southern state in India (Figure 1). Geographically, Tamil Nadu extends from approximately 8°5′ N to 13°35′ N latitude and between 76°15′ E and 80°20′ E longitude, covering a total area of 130,060 sq.km., which accounts for about 4 percent of India's total land area. The state is characterized by a diverse geography, including coastal plains, hills (Western and Eastern Ghats), and fertile river basins. Tamil Nadu experiences a tropical climate, influenced by the Bay of Bengal and the Indian Ocean, with distinct seasonal variations including hot summers, a monsoon season, and milder winters. The State lies at the southeastern extremity of the Indian Peninsula, bordered by Karnataka to the northwest, Andhra Pradesh to the north, the Bay of Bengal to the east, the Indian Ocean to the south, and Kerala State to the west. Tamil Nadu boasts a significant coastline stretching 1076 km along its eastern and southern boundaries.

The climate of Tamil Nadu is notably distinct from the general climate of the Indian subcontinent, characterized as semi-arid and tropical monsoon, influenced by its unique topographical features and geographical positioning. The long coastal stretch in the east, the hill orography of the Western Ghats along its western rim, and the extensive plains in the inland all play a significant role in shaping the State's climate. The State generally experiences tropical temperatures with minimal variation between summer and winter, maintaining relatively high temperatures and humidity throughout the year, except during the monsoon seasons. Summers are hot, with temperatures rising to 43 °C and typically extending from April to June. The coolest winter period is from November to February, with temperatures around 18 °C.

There are also indications of an increase in heavy rainfall events during the northeast monsoon season, while the southwest monsoon season may experience a slight decrease in rainfall. These climatic sensitivities underscore the importance of monitoring atmospheric pollutants, such as SO_2, which can exacerbate environmental and health issues in an already vulnerable region. The state is highly industrialized, with significant sectors including manufacturing, power generation (thermal power plants), textiles, and automobile industries, and firecracker industries, which are potential sources of atmospheric SO_2 emissions. Its complex interplay of urban centers, industrial zones, and agricultural lands makes it an ideal region for studying the dynamics of air pollution.

Data Sources

Data: The dataset, derived from the Sentinel-5P TROPOMI instrument, offers a high spatial resolution of 3.5 x 7 km, allowing for the detection of smaller SO_2 plumes. Near-real-time SO_2 data are available, enabling timely monitoring of events such as volcanic eruptions. The 'SO2_column_number_density' band was selected for focused analysis. A time series chart was generated using the 'ui.Chart.image.series' function in Google Earth Engine, illustrating temporal fluctuations in SO_2 levels across the study duration.

Boundary data for Tamil Nadu: A shapefile or feature collection representing the administrative boundary of Tamil Nadu will be imported into Google Earth Engine to clip the SO_2 data to the study area.

Methodology

The Sentinel-5P SO_2 dataset will be accessed through the Google Earth Engine (GEE) for the study period spanning January 1, 2024, to February 28, 2025. Spatial filtering will be applied by clipping the data to the administrative boundary of Tamil Nadu using a pre-defined shapefile. To ensure data reliability, a quality assurance (QA) threshold of 0.75 will be implemented, excluding low-quality or cloud-affected observations as per TROPOMI guidelines. Seasonal aggregation will be performed by computing the mean SO_2 concentrations for

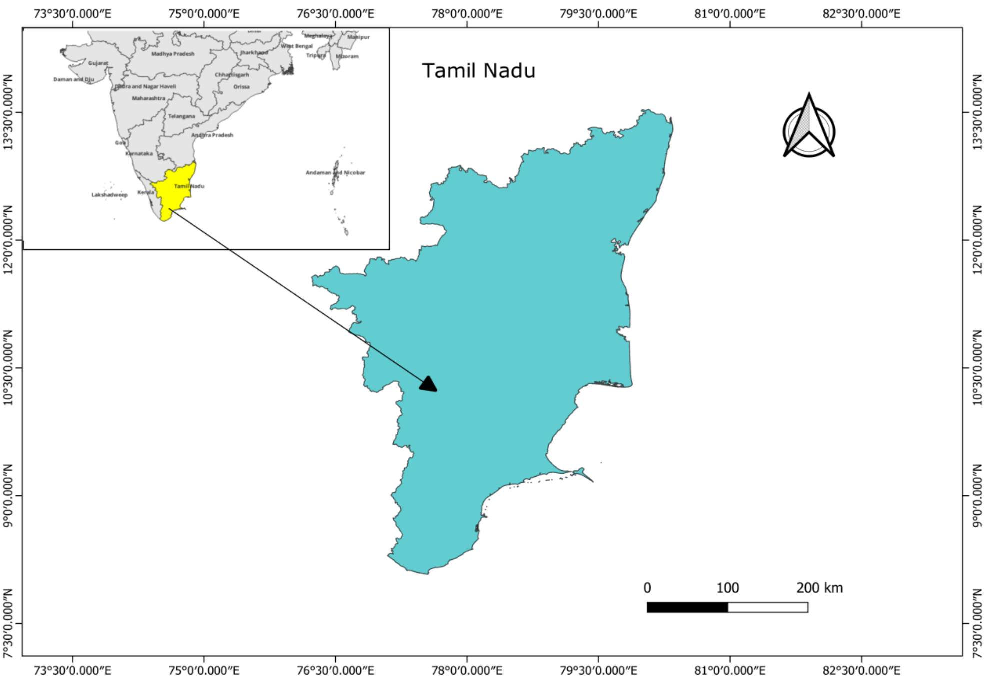

Figure 1: Study Area of Tamil Nadu, India.

summer, monsoon, and winter. Additionally, a time series analysis will be conducted by aggregating daily SO_2 values into monthly averages to capture temporal trends across the entire region. Seasonal SO_2 maps exported from GEE will be visualized in QGIS with cartographic elements. Monthly mean SO_2 data for the time series will be exported as comma-separated values and graphed for trend analysis.

·Spatial Analysis: Seasonal SO_2 concentration maps will be visually inspected to identify pollution hotspots and spatial distribution patterns across Tamil Nadu for each season.

·Temporal Analysis: The time-series chart will be examined to detect trends, fluctuations, and peak SO_2 levels during the 2024–2025 period. These temporal patterns will be cross-referenced with the seasonal maps to understand seasonal influences.

·Interpretation: The spatial and temporal findings will be interpreted considering the region's industrial activities, meteorological factors such as wind and rainfall, and significant events that may impact SO_2 emissions or atmospheric dispersion within Tamil Nadu.

RESULTS

This section presents the findings from the spatial and temporal analysis of SO_2 concentrations across Tamil Nadu, India, from March 2024 to February 2025. The results are categorized into seasonal pollution maps and a monthly average time series chart.

Spatial Distribution of SO_2 Pollution

The seasonal SO_2 pollution concentration maps (Figures 2, 3, and 4: Summer, Monsoon, and Winter) reveal distinct spatial patterns across Tamil Nadu. In all three seasons, a prominent hotspot of high SO_2 concentration is consistently observed in the northwestern part of Tamil Nadu, particularly concentrated around the Neyveli region and its surrounding industrial belt.

- Summer (March–May 2024) (Figure 2): The summer map indicates a pronounced area of high SO_2 concentration in the northeastern region, with the highest values depicted in red and orange, gradually transitioning to lower concentrations (blue and purple) towards the north and western parts of the state. The extent and intensity of the hotspot appear to be at their peak during this period.
- Monsoon (June–October 2024) (Figure 3): During the monsoon season, the overall SO_2 concentrations across Tamil Nadu generally appear to be lower compared to the summer months. While the northeastern hotspot remains

identifiable, its intensity (represented by lighter orange/yellow tones rather than dark red) and spatial extent appear to be slightly reduced. Much of the state shows low SO_2 levels, depicted in various shades of blue and purple.

- Winter (November 2024 – February 2025) (Figure 4): The winter map shows a notable increase in SO_2 concentration in the northeastern hotspot compared to the monsoon season, although it might not reach the peak levels observed in summer. The area of elevated SO_2 is visible in red and orange, suggesting a resurgence of pollution during this cooler period. Similar to other seasons, the rest of Tamil Nadu maintains relatively low SO_2 levels.

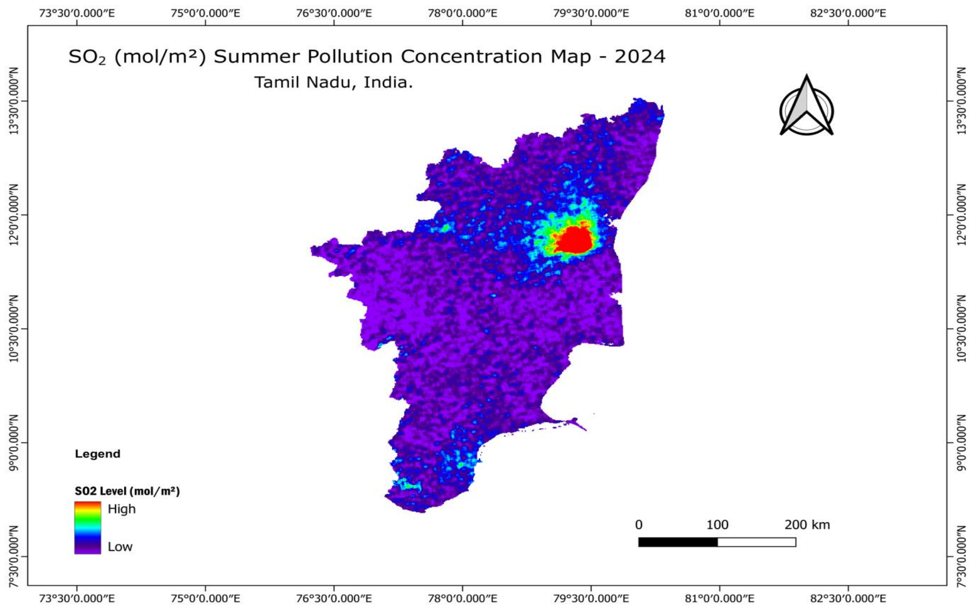

Figure 2: Mean SO_2 *(mol/m²) Summer Pollution Concentration Map – 2024*

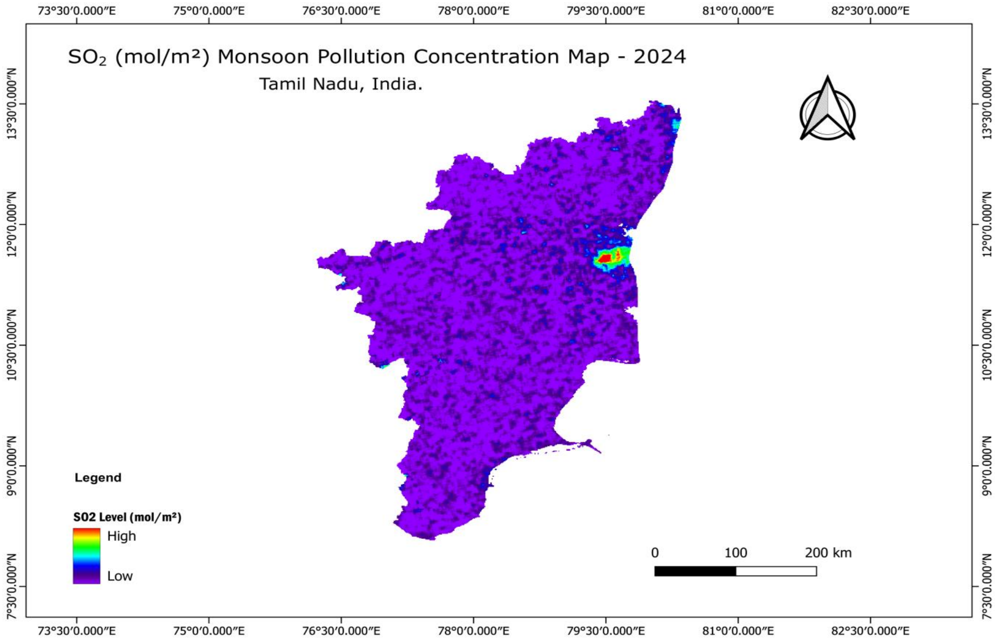

Figure 3: Mean SO_2 *(mol/m²) Monsoon Pollution Concentration Map – 2024.*

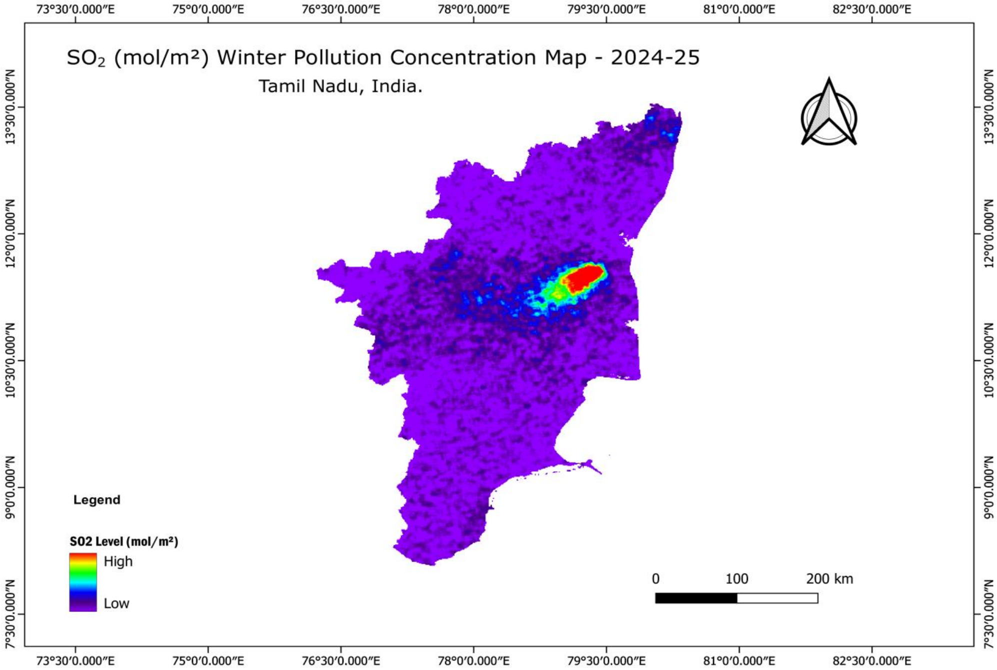

Figure 4: Mean SO_2 ***(mol/m²) Winter Pollution Concentration Map - 2024-25.***

Temporal Variation of SO_2 Concentration

The monthly average SO_2 concentration time series chart for Tamil Nadu (Figure 5) provides a detailed overview of temporal variations from March 2024 to February 2025. The time series analysis of SO_2 concentrations over Tamil Nadu from March 2024 to February 2025 reveals clear seasonal trends driven by climatic conditions and anthropogenic activities.

Summer Season: SO_2 concentrations peaked in April 2024 at approximately 0.00037 mol/m², driven by intense industrial activities, energy production, and dry, stagnant atmospheric conditions typical of summer. By May 2024, concentrations started to decline as temperatures began to moderate.

Monsoon Season: During the monsoon months, SO_2 levels are reduced significantly due to the cleansing effect of rainfall and active wind patterns. Concentrations dropped to 0.00027 mol/m² in June and further to 0.00024 mol/m² by September 2024. A slight post-monsoon increase to 0.00026 mol/m² was noted in October 2024.

Winter Season: In winter, SO_2 concentrations gradually declined, reaching a low of 0.00019 mol/m² in January 2025. This was due to cooler temperatures, lower energy demand, and the residual effects of the monsoon. By February 2025, there was a minor increase to 0.00022 mol/m², likely due to a resurgence in industrial emissions.

DISCUSSION

The results of this study consistently highlight that the northeastern region of Tamil Nadu has a significant hotspot for SO_2 pollution. This finding aligns with the known industrial landscape of the region, which hosts numerous power plants, refineries, chemical industries, and manufacturing units. These industrial activities, heavily reliant on fossil fuel combustion, are primary contributors to atmospheric SO_2 emissions.

Seasonal Variations in SO_2 Levels

Summer Season (March to May): The sulphur dioxide (SO_2) concentrations in Tamil Nadu were significantly influenced by emissions from major thermal power plants. Higher temperatures and increased energy demand for cooling during this period likely lead to intensified operations in thermal power plants and industries, consequently increasing SO_2 emissions. The Neyveli Thermal Power Plant emerged as the primary contributor, followed by the Mettur Thermal Power Plant in Salem, the North Chennai Thermal Power Plant, and the Tuticorin (Thoothukudi) Thermal Power Station.

In summer, the SO_2 emissions from the Neyveli Thermal Power Plant predominantly dispersed towards the north and partially towards the south, driven by prevailing wind patterns. The highest concentrations were recorded in the eastern part

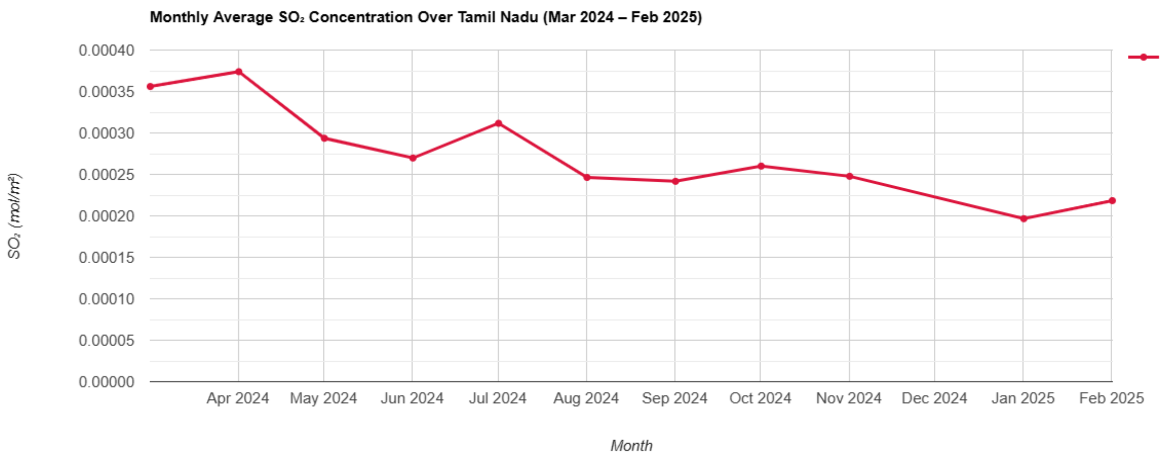

Figure 5: Monthly Average* SO_2 concentration *Over Tamil Nadu (Mar 2024 – Feb 2025).

of Cuddalore district, with further dispersion extending into Villupuram, Kallakurichi, Dharmapuri, Vellore, and Tiruvannamalai districts.

Similarly, in the southern region, the Tuticorin Thermal Power Station significantly elevated SO_2 levels within the Thoothukudi district and its surroundings. Apart from these major power plants, several other industrial operations across Tamil Nadu also contributed to notable SO_2 pollution during the summer months, further exacerbating regional air quality concerns. Furthermore, meteorological conditions typical of summer, such as stable atmospheric conditions and lower wind speeds, can lead to the stagnation of pollutants, preventing their efficient dispersion and resulting in higher concentrations at ground level.

Monsoon Season: Conversely, the reduction in SO_2 concentrations during the monsoon season (June to October) is a well-documented phenomenon for air pollutants. The scavenging effect of rainfall effectively washes SO_2 out of the atmosphere, leading to lower ambient concentrations. Increased wind speeds associated with monsoon systems can also contribute to better dispersion of pollutants.

During the monsoon season (June to October), the dispersion of SO_2 emissions from the Neyveli Thermal Power Plant is predominantly directed towards the Bay of Bengal, driven by the prevailing southwest monsoon winds. As a result, the pollutant plume often reaches the coastal areas and dissipates over the sea, reducing its impact on inland regions.

During this period, SO_2 pollution from Neyveli primarily affects only the Cuddalore district with minimal dispersion beyond this zone. Similarly, emissions from the North Chennai Thermal Power Plant are also reduced, with only a limited and localized impact.

Overall, during the monsoon season, Tamil Nadu experiences lower SO_2 concentrations across the state due to frequent rainfall, higher humidity, and enhanced atmospheric cleansing. These meteorological conditions facilitate the washout of pollutants, thereby mitigating the extent of air pollution during this season. The slight resurgence in July, as seen in the time series, might warrant further investigation into specific industrial activities or localized meteorological events during that month.

Winter Season: The increase in SO_2 levels during winter (November-February), although not as high as in summer, is also a common trend in many parts of India. During winter, cooler temperatures often lead to an inversion layer in the atmosphere, trapping pollutants close to the ground. Additionally, reduced vertical mixing and lower wind speeds can hinder the dispersion of pollutants, leading to their accumulation. Increased demand for heating (though less prevalent in Tamil Nadu compared to northern India, industrial heating could still play a role) and the burning of agricultural waste (though less directly linked to SO_2 from industrial sources, it can contribute to overall air quality issues) might also contribute.

During the winter season, following the post-monsoon period, the dispersion pattern of SO_2 emissions from the Neyveli Thermal Power Plant shifts predominantly towards southern Tamil Nadu. The pollutant plume extends over Perambalur, Ariyalur, Namakkal, Tiruchirappalli, and partially over Salem district.

The Mettur Thermal Power Plant in Salem contributes to localized SO_2 pollution, primarily affecting the surrounding regions with limited dispersion. Similarly, in Chennai, emissions from the North Chennai Thermal Power Plant continue to affect nearby areas, although with reduced intensity compared to the summer months.

In contrast, the SO_2 emissions from the Tuticorin (Thoothukudi) Thermal Power Station tend to decline significantly during the winter season, contributing less to regional air pollution. Overall, SO_2 concentrations across Tamil Nadu are generally lower in winter, attributed to meteorological factors such as lower temperatures, higher humidity, and altered wind patterns that limit the long-range transport of pollutants.

Spatial and Temporal Dispersion Patterns

The time series chart (Figure 5) corroborates the patterns observed in the seasonal maps. The peak in April 2024 corresponds to the summer high, and the subsequent dip from May to October reflects the cleansing effect of the monsoon. The gradual rise from November onwards signifies the onset of winter atmospheric conditions, which are conducive to pollutant accumulation. The consistency between the spatial maps and the time series chart strengthens the validity of the findings.

Future research could delve deeper into correlating these SO_2 patterns with specific industrial clusters, meteorological data (including wind speed, direction, rainfall, and boundary layer height), and significant policy interventions or economic shifts in Tamil Nadu. High-resolution dispersion modelling could further pinpoint the precise sources and their contributions to the observed hotspots. The information derived from this study can serve as a crucial input for local environmental agencies in developing targeted pollution control strategies and assessing the effectiveness of existing air quality regulations in Tamil Nadu.

CONCLUSION

In summary, this study provides valuable insights into the growing body of research on air quality monitoring in South Asian countries, specifically focusing on the spatial and seasonal dynamics of sulphur dioxide (SO_2) concentrations in Tamil Nadu. By leveraging advanced remote sensing data and GIS analytical methods, the research effectively identifies key pollution hotspots, dominant industrial contributors, and the seasonal variability of SO_2 emissions across the state.

These findings provide a scientific basis for developing targeted, evidence-based environmental management policies that aim to mitigate air pollution and protect public health. Moreover, the methodologies and outcomes of this research can inform sustainable development strategies and support regulatory frameworks in Tamil Nadu and similar industrial regions. Future studies that integrate meteorological data, emission inventories, and predictive modeling will further enhance our understanding of air pollution dynamics and assist policymakers in designing effective intervention measures.

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