

Monitoring Air Pollution Dynamics of NO₂ and SO₂ in Sri Lanka Using Sentinel-5P from 2019 to 2024

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Keywords: Sentinel-5P; Nitrogen Dioxide (NO₂); Sulfur Dioxide (SO₂); GIS; Google Earth Engine (GEE)

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Abstract:	Highlights • Six years of satellite data were used to map nitrogen dioxide and sulfur dioxide across all 25 districts of Sri Lanka. • Nitrogen dioxide was persistently highest along the urbanised western coastal corridor around Colombo. • Sulfur dioxide hotspots clustered near thermal power plants and industrial zones in Puttalam and Kalutara. • Monsoon rains lowered both pollutants, and the 2020 pandemic lockdown caused a sharp but brief fall in nitrogen dioxide. • Free satellite data offer a low-cost way to track air quality where ground monitoring stations are scarce.
Suggested Reviewers:	Aneesh Mathew, PhD Assistant Professor, National Institute of Technology Tiruchirappalli aneesh@nitt.edu Dr. Mathew is lead author of a Sentinel-5P TROPOMI hotspot analysis of urban air quality in Indian cities during COVID-19 (Scientific Reports, 2024). His work combines GIS, remote sensing and air pollution in South Asia, which matches this study's district-level NO₂/SO₂ hotspot mapping, monsoon seasonality and lockdown signal in Sri Lanka. Daniele Oxoli, PhD Assistant Professor, Politecnico di Milano DIIR: Politecnico di Milano Dipartimento di Ingegneria Civile e Ambientale daniele.oxoli@polimi.it Dr. Oxoli has assessed how well Sentinel-5P represents ground-level air quality, including during the COVID-19 lockdown (ISPRS Archives, 2020). He is well placed to judge the column-to-surface ppb conversion, the comparison with ground stations, and the interpretation of the lockdown-period NO₂ decline.

	Marina Virghileanu, PhD Assistant Professor, University of Bucharest Faculty of Geography: Universitatea din Bucuresti Facultatea de Geografie marina.virghileanu@geo.unibuc.ro Dr. Virghileanu is lead author of a widely cited Sentinel-5P study of NO₂ over Europe during the COVID-19 outbreak (Remote Sensing, 2020). Her experience with multi-temporal satellite mapping in GIS fits the monthly raster composites and NRTI/OFFL comparison in this manuscript.
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Title Page

Monitoring Air Pollution Dynamics of NO₂ and SO₂ in Sri Lanka Using Sentinel-5P from 2019 to 2024

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Highlights

- Six years of satellite data were used to map nitrogen dioxide and sulfur dioxide across all 25 districts of Sri Lanka.
- Nitrogen dioxide was persistently highest along the urbanised western coastal corridor around Colombo.
- Sulfur dioxide hotspots clustered near thermal power plants and industrial zones in Puttalam and Kalutara.
- Monsoon rains lowered both pollutants, and the 2020 pandemic lockdown caused a sharp but brief fall in nitrogen dioxide.
- Free satellite data offer a low-cost way to track air quality where ground monitoring stations are scarce.

Statements and Declarations

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Author contributions (CRediT): P.V.U. Kalpana: Conceptualization, Methodology, Software, Formal analysis, Investigation, Data curation, Writing – original draft preparation, Visualization. P.G.R.N.I. Pussella: Conceptualization, Supervision, Validation, Writing – review and editing. J.K. Gunatilake: Conceptualization, Supervision, Validation, Writing – review and editing. All authors read and approved the final manuscript.

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Monitoring Air Pollution Dynamics of NO₂ and SO₂ in Sri Lanka Using Sentinel-5P from 2019 to 2024

Abstract

Air pollution monitoring in developing nations is constrained by sparse ground-based infrastructure, making satellite remote sensing an essential alternative. This study analysed the spatiotemporal dynamics of nitrogen dioxide (NO₂) and sulfur dioxide (SO₂) across all 25 administrative districts of Sri Lanka from 2019 to 2024 using Sentinel-5P TROPOspheric Monitoring Instrument (TROPOMI) Level-3 satellite data integrated with Geographic Information Systems (GIS). Monthly raster maps were generated from Near Real-Time (NRTI) and Offline (OFFL) datasets processed through Google Earth Engine, with column densities converted to estimated surface concentrations in parts per billion (ppb). Results revealed persistently elevated NO₂ concentrations in the western coastal corridor (Colombo, Gampaha, and Kalutara), attributable to high traffic density, urban growth, and industrial activity. SO₂ hotspots were concentrated around industrial point sources in Puttalam and Kalutara, particularly near thermal power generation facilities. Both pollutants exhibited pronounced seasonal variability driven by southwest and northeast monsoon patterns, with lower concentrations recorded during high-rainfall months. A marked reduction in NO₂ was observed during the 2020 COVID-19 lockdown period, corroborating the anthropogenic origin of urban emissions. Comparison of NRTI and OFFL products demonstrated complementary utility for short-term event detection and long-term trend analysis respectively. These findings provide a cost-effective, spatially comprehensive framework for national air quality management and environmental policy planning in Sri Lanka.

Keywords: Sentinel-5P; Nitrogen Dioxide (NO₂); Sulfur Dioxide (SO₂); GIS; Google Earth Engine (GEE)

1. Introduction

Air pollution is among the most pressing environmental concerns worldwide, affecting public health, ecosystem stability, and global climate dynamics (Jia, 2019). Nitrogen dioxide (NO₂) and sulfur dioxide (SO₂) are among the most significant air pollutants, both harmful to respiratory health (Chattopadhyay et al., 2010) and reactive precursors to secondary pollutants such as acid rain and particulate matter. NO₂ originates mainly from

vehicle emissions, industrial combustion, and power generation, whereas SO₂ is linked predominantly to the combustion of fossil fuels, particularly coal and oil, and to specific industrial processes. Beyond their direct toxicity, both gases participate in atmospheric reactions that further degrade air quality (Kumar et al., 2016).

In Sri Lanka, rapid urban growth, industrialization, and rising energy consumption have driven increasing NO₂ and SO₂ emissions (Manawadu et al., 2009). Urban centres such as Colombo, Gampaha, and Kalutara experience high traffic and industrial emissions, while Puttalam and Trincomalee are important emission sources linked to power generation and maritime activity. However, the country's sparse network of ground-based air-quality monitoring stations limits the ability to characterise pollution trends comprehensively, particularly outside major cities (Samarakkody & Fernando, n.d.).

Remote sensing combined with Geographic Information Systems (GIS) offers an effective means of overcoming the limitations of sparse ground-based monitoring (Themistocleous et al., 2008). The Sentinel-5 Precursor (Sentinel-5P) satellite, launched by the European Space Agency under the Copernicus programme, carries the TROPOspheric Monitoring Instrument (TROPOMI), which provides daily global measurements of NO₂ and SO₂ at spatial resolutions as fine as 3.5 km² (van Geffen et al., 2022). Sentinel-5P/TROPOMI data have been applied increasingly to monitor pollutant dynamics across diverse settings, from volcanic SO₂ degassing (Theys et al., 2019) and urban NO₂ retrieval validation against airborne and ground-based instruments (Judd et al., 2020), to lockdown-period air-quality assessments in Europe and South Asia (Oxoli et al., 2020; Virghileanu et al., 2020). Studies combining Sentinel-5P with GIS have further demonstrated its capacity to map district-level pollutant levels, examine seasonal trends, and identify persistent hotspots even where ground infrastructure is absent (Al-Alola et al., 2022).

Despite this growing body of work, dedicated, multi-year assessments of the spatial and temporal dynamics of NO₂ and SO₂ across the whole of Sri Lanka remain scarce. Existing national studies tend to rely on short observation windows or localised case studies focused on Colombo and its immediate surroundings, frequently excluding rural and remote districts (Manawadu et al., 2009), and the integration of seasonal patterns into national air-quality management planning remains limited (Central Environmental Authority, 2023). No published study has yet combined multi-year Sentinel-5P NRTI and OFFL Level-3 data with a GIS-based framework to characterise NO₂ and SO₂ dynamics consistently across all 25 administrative districts of Sri Lanka.

This study addresses that gap by combining six years (2019–2024) of Sentinel-5P OFFL and NRTI Level-3 data with a GIS-based framework to characterise NO₂ and SO₂ dynamics across all 25 administrative districts, focusing specifically on these two pollutants rather than the broader suite of criteria pollutants such as particulate

matter (PM_{2.5}), ozone (O₃), or carbon monoxide (CO). Its goal is to map pollutant distributions, characterise seasonal and monsoon-driven variability, identify persistent hotspots, compare the complementary strengths of the NRTI and OFFL products, and generate evidence to support national and district-level air-quality management.

The specific objectives are to:

- Creating maps that show pollutant levels on an annual basis and by district.
- Examining how seasonal changes and weather patterns affect NO₂ and SO₂ levels.
- Identifying and illustrating areas with high pollution levels through GIS spatial analysis.
- Analyzing the results from the NRTI and OFFL datasets to estimate pollutants.
- Emphasizing important insights for managing emissions and planning areas for development.

2. Methodology

2.1 Study Area

Sri Lanka, a tropical island in the Indian Ocean, was chosen for this research because of its rich ecological diversity, varied climate, and growing urbanization. The country is divided into 25 districts, each having unique urban, rural, and industrial features that affect air quality. Sri Lanka has two main monsoon seasons: the southwest monsoon from May to September and the northeast monsoon from December to February. There are also two inter-monsoon periods. These weather patterns play a significant role in how air pollutants are spread, collected, and changed in the environment. Sri Lanka presents a unique opportunity to study how the levels of nitrogen dioxide (NO₂) and sulfur dioxide (SO₂) change over time and in different locations.

2.2 Data Sources

This research mainly used data from the Sentinel-5P satellite, which was launched by the European Space Agency as part of the Copernicus program. Sentinel-5P has the TROPospheric Monitoring Instrument (TROPOMI) on board, allowing it to observe atmospheric gases like NO₂ and SO₂ every day across the globe (Judd et al., 2020). This analysis utilised two types of Level-3 processed products: the Near-Real-Time (NRTI) product and the Offline (OFFL) product. The NRTI dataset is quickly available and provides timely updates that are advantageous for short-term evaluations. In contrast, the OFFL dataset goes through more thorough post-processing, making it better suited for in-depth, long-term trend analysis. Both datasets provide total column

densities of NO₂ and SO₂ measured in mol/m², which were later converted into parts per billion (ppb) for easier visualization (Oxoli et al., 2020).

2.3 Data Acquisition and Preprocessing

Satellite data was obtained by accessing Sentinel-5P Level-3 products via the Google Earth Engine (GEE) platform (Gorelick et al., 2017). Each month, daily imagery for each pollutant was filtered to ensure that only valid observations were included within the appropriate time frame. Cloud interference and any negative or invalid readings were eliminated by applying quality masks included in the dataset. The study area was defined by the geographic boundaries of Sri Lanka, using a rectangular shape based on the country's latitude and longitude limits.

After extracting and cleaning the data, the daily images for each month were combined to determine the average for that month. This step made sure that the resulting raster images accurately showed the average distribution of pollutants for each month, reducing the impact of short-term changes caused by weather or missing data. The column number densities (mol/m²) were transformed into estimated surface-level concentrations in parts per billion (ppb) by applying a standardised estimate of air column density adjusted for the average elevation of Sri Lanka. This change helped ensure that maps were interpreted and visualized in a consistent way. The overall methodological framework is shown in Fig. 1.

Total-column densities (Ω , mol m⁻²) were converted to estimated surface-level volume mixing ratios (ppb) using a simplified boundary-layer approach adapted from established column-to-surface conversion methods (Boersma et al., 2004; Theys et al., 2019). The pollutant mass was assumed to be uniformly distributed within a well-mixed boundary layer of height H , and the resulting mass concentration was converted to a volume mixing ratio using the ideal gas law:

$$C \text{ (ppb)} = \frac{\Omega \times M \times R \times T}{H \times P \times 10^{-9}} \quad (1)$$

where M is the molar mass of the target gas (46.01 g mol⁻¹ for NO₂; 64.07 g mol⁻¹ for SO₂), R is the universal gas constant, T and P are the mean boundary-layer temperature and pressure for Sri Lanka, and H is a fixed boundary-layer height (assumed constant at approximately 1,000 m in the absence of contemporaneous radiosonde profiles). This approach assumes a well-mixed, uniform vertical column and a constant boundary-layer height, and therefore carries greater uncertainty in areas of complex terrain, such as the central highlands (Nuwara Eliya, Badulla), where boundary-layer height and atmospheric mixing vary more strongly with elevation; the implications of this assumption are discussed further in Section 4.

To assess the plausibility of the converted values, estimated ppb concentrations at the grid cells nearest to two permanent ground stations, Colombo (Battaramulla) and Kandy, were compared against Central Environmental Authority (CEA) continuous ambient air-quality monitoring records for the same months (Central Environmental Authority, 2023) [A previous validation of these data reported good agreement for NO₂, with Mean Absolute Percentage Error (MAPE) of 12.4% (OFFL) and 15.2% (NRTI) at Battaramulla and 18.6% (OFFL) and 21.7% (NRTI) at Kandy, and Root Mean Squared Error (RMSE) of 1.79–2.89 ppb. Agreement for SO₂ was weaker, with MAPE of 18.9–31.6% and RMSE of 2.63–3.67 ppb. The OFFL product consistently outperformed NRTI, and errors were lower in flat, urban Battaramulla than in topographically complex Kandy (Kalpana et al., 2025).]. This comparison is indicative rather than a full validation exercise, and extending it to additional stations and years is identified as a priority for future work (Section 5.2).

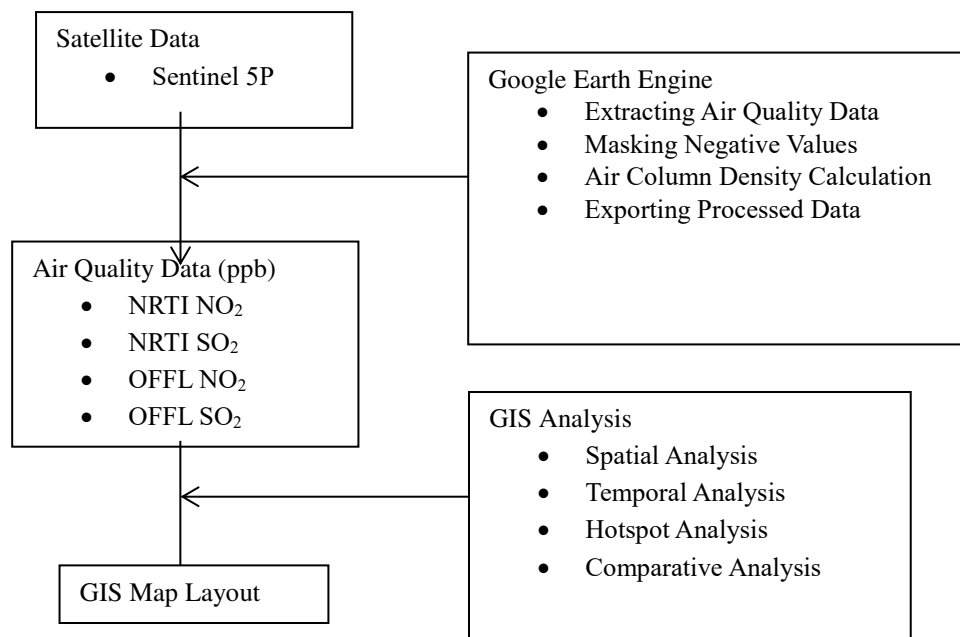


Fig. 1 Methodological framework

2.4 Raster Export and GIS Integration

The monthly raster files were prepared and then exported from the Earth Engine platform in GeoTIFF format. The files were imported into GIS software, ArcGIS, to prepare for styling and map layout. In the GIS environment, each raster was represented using a set of classification ranges that were suitable for the images. A legend with five colours, ranging from yellow to dark red, was used to show increasing levels of concentration. The same

colour scale was applied consistently throughout all months and years, allowing for easy visual comparison across the whole study period.

The data for each year was arranged into a single map layout panel, showcasing all twelve-monthly raster images in a 3×4 grid format. The panels featured common map elements like scale bars, north arrows, geographic reference grids, and legends. The designs were created to ensure clarity while highlighting changes in pollutant levels over time and across different locations. Titles and captions that specify the type of pollutant, the year, and the source of the data were also included for accurate reference.

2.5 Hotspot Identification and Seasonal Interpretation

This study does not involve statistical hotspot detection; however, by visually inspecting the raster maps, it was managed to identify areas with consistently high concentrations, which are called hotspots (Pandey et al., n.d.). Districts like Colombo, Gampaha, and Kalutara have shown higher levels of NO₂ over various months and years. In a similar way, the levels of SO₂ were often highest in industrial areas like Puttalam and certain sections of the Southern coastal region. The monthly layouts were enabled to see how pollutant levels change with the seasons, showing lower concentrations during the monsoon and higher levels in the less humid months.

During the southwest monsoon, which occurs from May to September, the maps indicated lower levels of NO₂ in many areas of the western and southern regions. This decrease is probably a result of the cleansing effect of rainfall in the atmosphere. During the dry season, which lasts from January to April, pollutant levels seemed to be more concentrated, especially in urban areas and places with high population density. The seasonal patterns offered important insights into how weather conditions influence air pollution levels in the area.

2.6 Output Format and Presentation

All annual layout panels were exported in high-resolution JPEG or PDF format. These formats are intended for inclusion in the results section and can also be used in presentations or reports. The final visualizations were created to serve as independent outputs that clearly show spatial and temporal patterns in pollutant concentrations, without needing a lot of technical details to understand them.

Every layout shown:

- The geographic area of Sri Lanka
- A series of NO₂ or SO₂ maps over a 12-month period.
- Uniform colour legends and classification intervals.

- Elements that provide geographic references for orientation.

This method enabled a thorough comparison over time and space, revealing patterns that might not be as noticeable in tables or statistics alone.

3. Results

3.1 Overview of NO₂ Distribution Patterns (2019–2024)

Sentinel-5P NRTI data analysis revealed clear regional and seasonal NO₂ variations across Sri Lanka (2019–2024; Figs. 2–13). Monthly maps showed pollutant changes driven by urban activities, weather, and topography. Western and southwestern districts consistently exhibited elevated NO₂, particularly in the Colombo–Gampaha–Kalutara corridor—Sri Lanka's most urbanized and industrialized region, characterised by high population density, traffic, and industrial emissions.

In 2019, January–April observations showed significant NO₂ hotspots in Colombo and Kalutara (3–5 ppb, highest category). May–August monsoon months brought notable decreases, especially in coastal areas, reflecting rainfall's cleansing effect and atmospheric mixing.

Conversely, northern and eastern districts (Mullaitivu, Trincomalee, Batticaloa) consistently exhibited lower NO₂ (0–1 ppb) due to lower population density and reduced industrialization. Occasional dry season increases likely reflected regional air transport or local traffic changes.

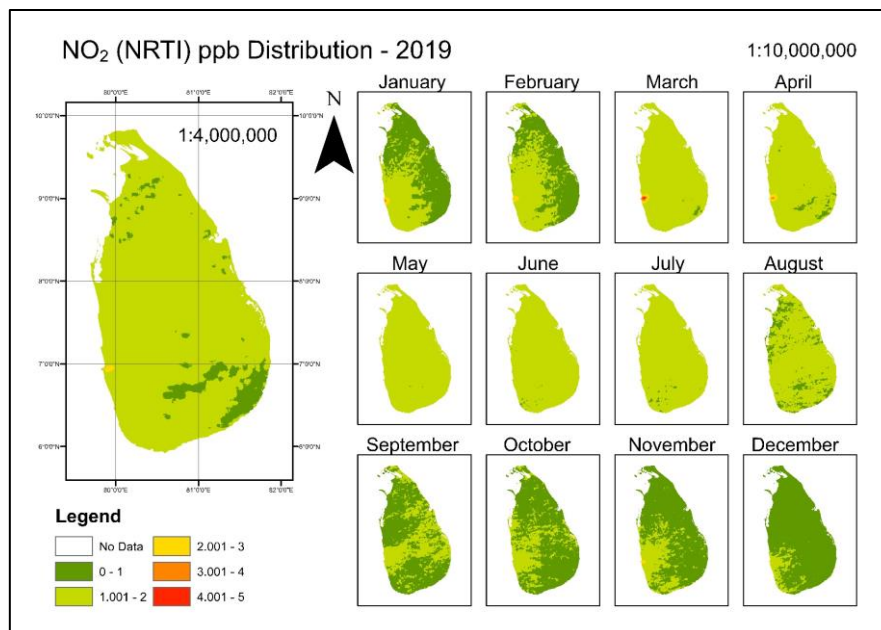


Fig. 2 Monthly Nitrogen Dioxide (NO₂) concentration maps for Sri Lanka in 2019, based on Sentinel-5P Near Real-Time (NRTI) Level-3 satellite observations

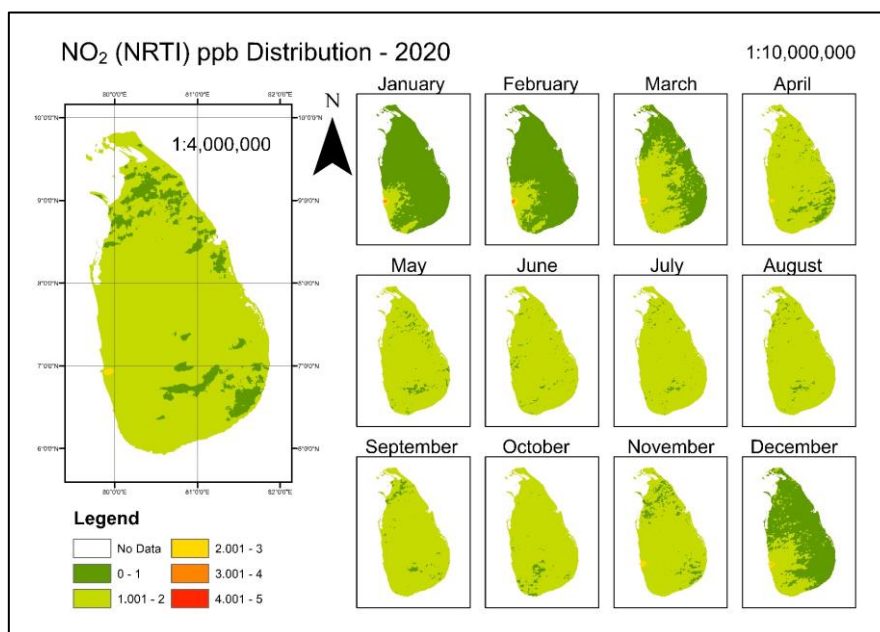


Fig. 3 Monthly Nitrogen Dioxide (NO₂) concentration maps for Sri Lanka in 2020, based on Sentinel-5P Near Real-Time (NRTI) Level-3 satellite observations

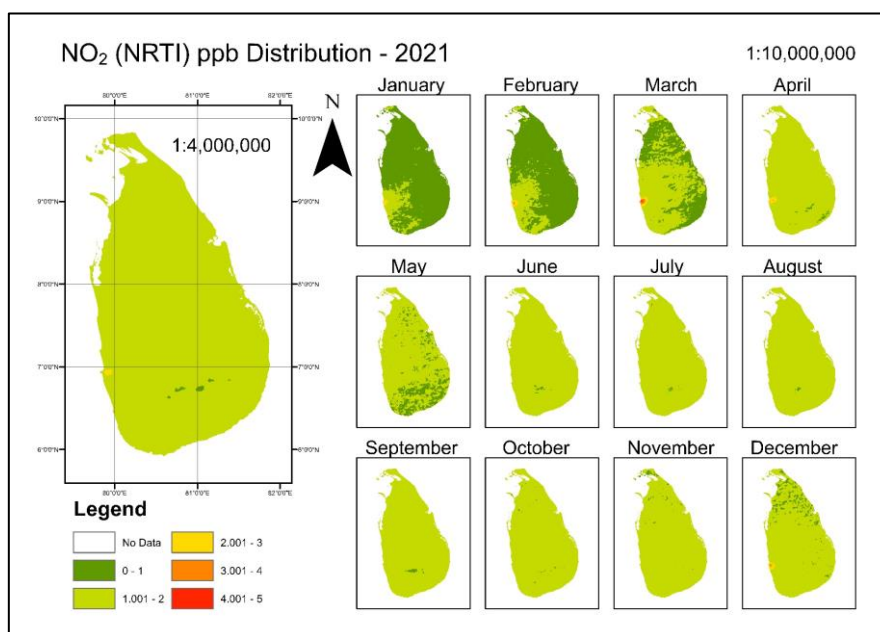


Fig. 4 Monthly Nitrogen Dioxide (NO₂) concentration maps for Sri Lanka in 2021, based on Sentinel-5P Near Real-Time (NRTI) Level-3 satellite observations

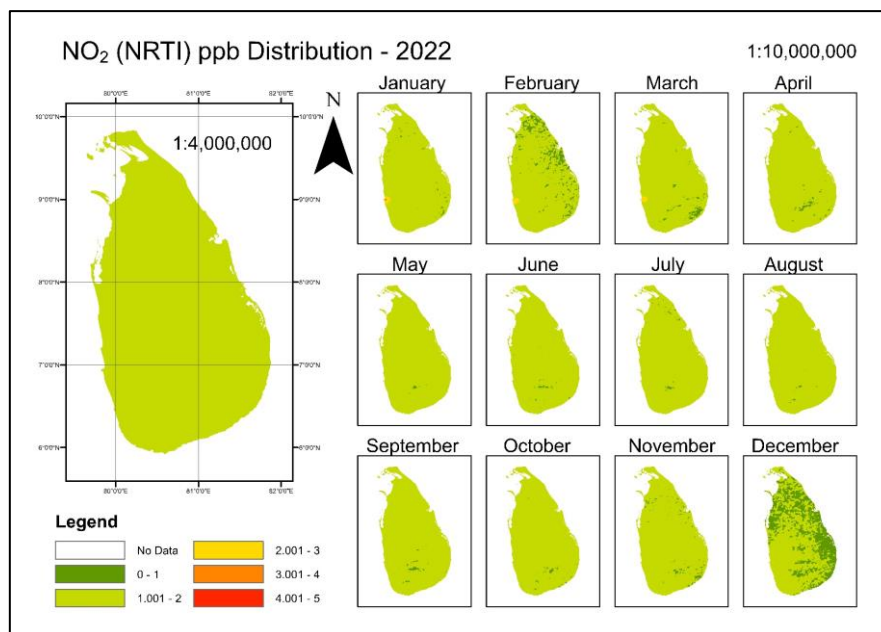


Fig. 5 Monthly Nitrogen Dioxide (NO₂) concentration maps for Sri Lanka in 2022, based on Sentinel-5P Near Real-Time (NRTI) Level-3 satellite observations

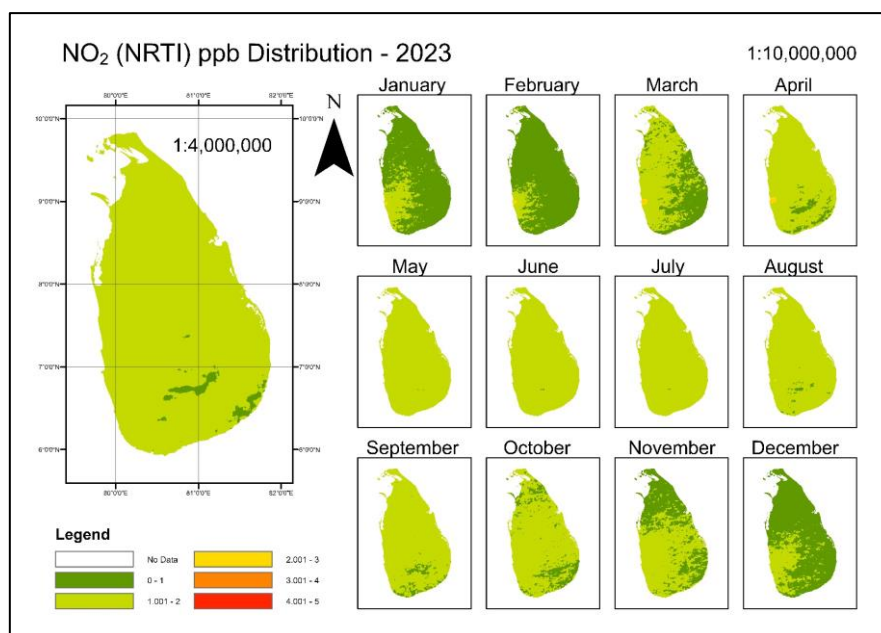


Fig. 6 Monthly Nitrogen Dioxide (NO₂) concentration maps for Sri Lanka in 2023, based on Sentinel-5P Near Real-Time (NRTI) Level-3 satellite observations

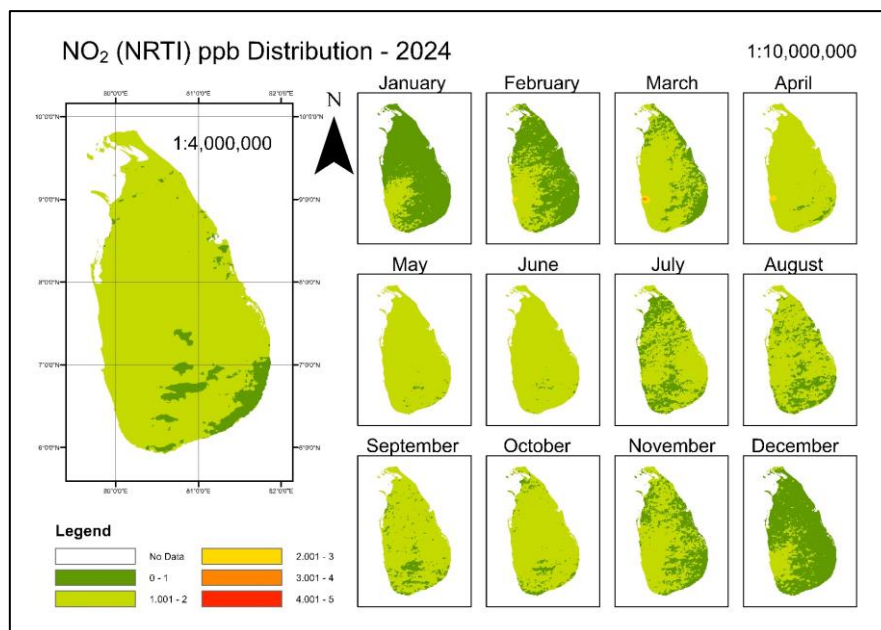


Fig. 7 Monthly Nitrogen Dioxide (NO₂) concentration maps for Sri Lanka in 2024, based on Sentinel-5P Near Real-Time (NRTI) Level-3 satellite observations

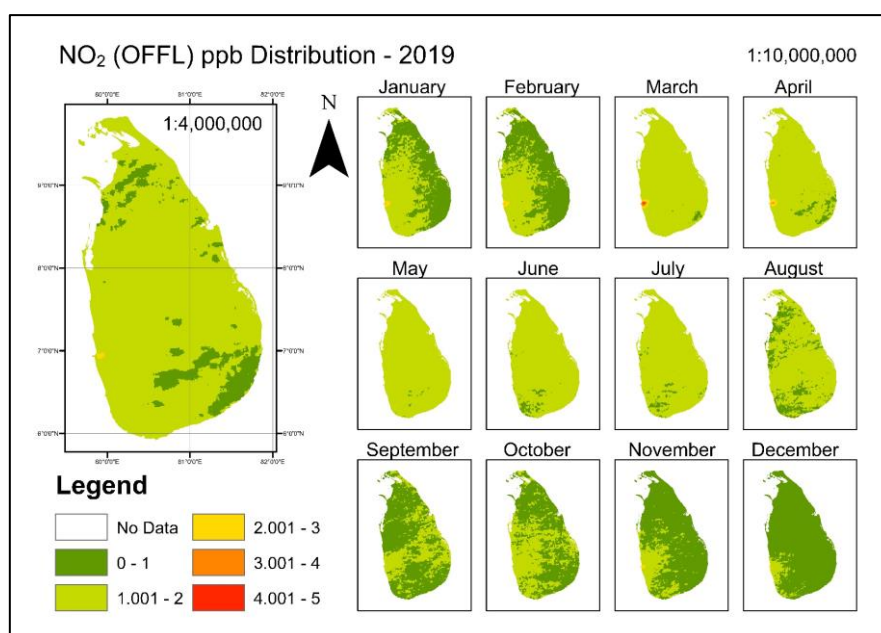


Fig. 8 Monthly Nitrogen Dioxide (NO₂) concentration maps for Sri Lanka in 2019, based on Sentinel-5P Offline (OFFL) Level-3 satellite observations

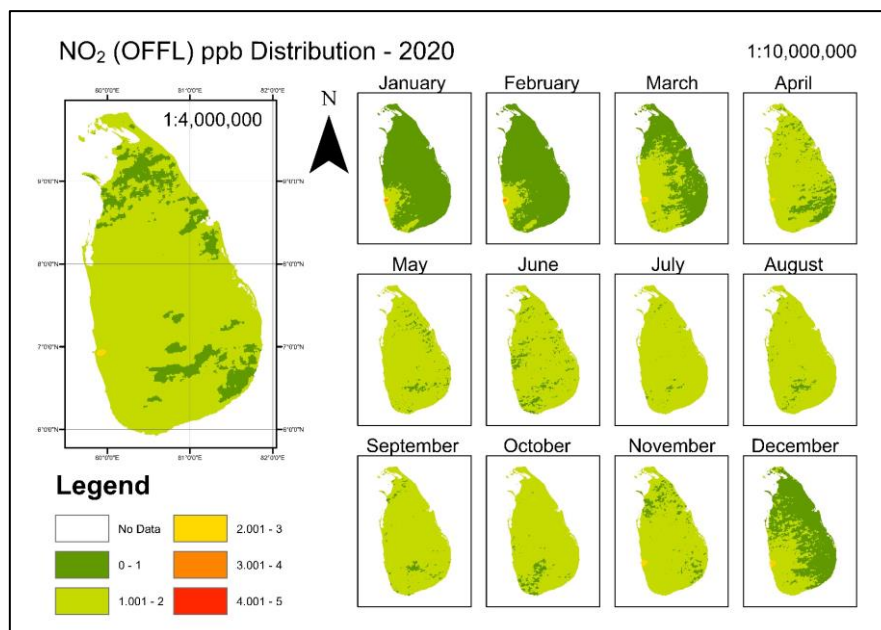


Fig. 9 Monthly Nitrogen Dioxide (NO₂) concentration maps for Sri Lanka in 2020, based on Sentinel-5P Offline (OFFL) Level-3 satellite observations

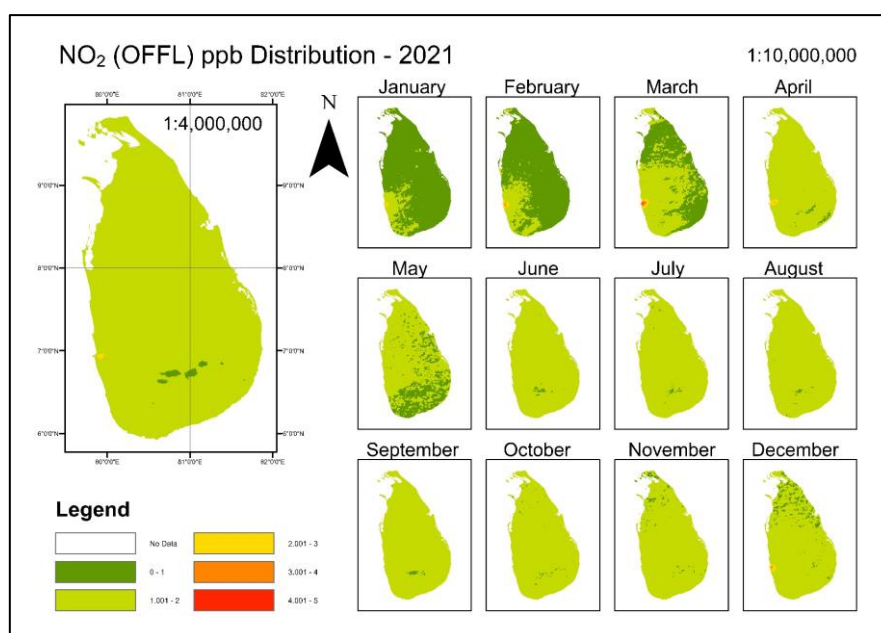


Fig. 10 Monthly Nitrogen Dioxide (NO₂) concentration maps for Sri Lanka in 2021, based on Sentinel-5P Offline (OFFL) Level-3 satellite observations

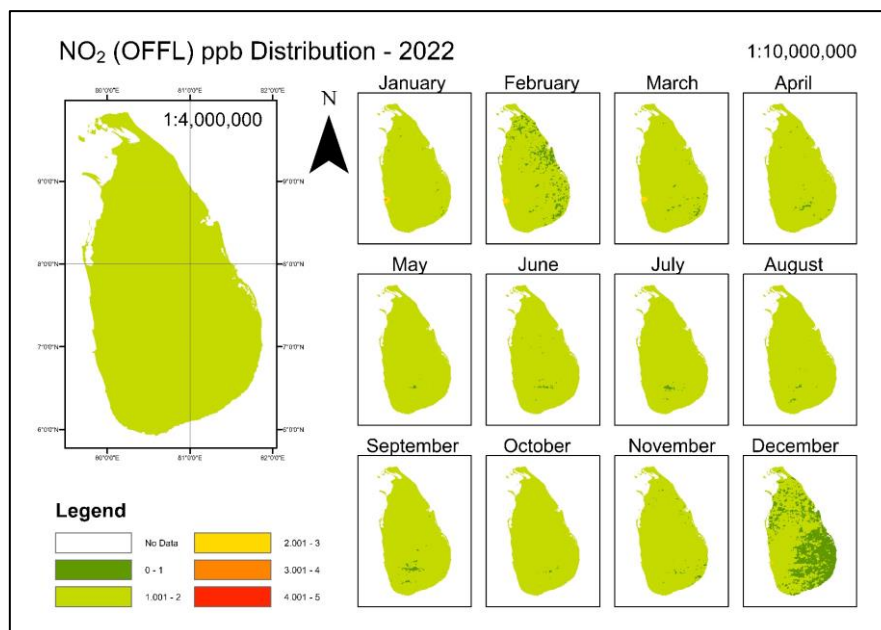


Fig. 11 Monthly Nitrogen Dioxide (NO₂) concentration maps for Sri Lanka in 2022, based on Sentinel-5P
Offline (OFFL) Level-3 satellite observations

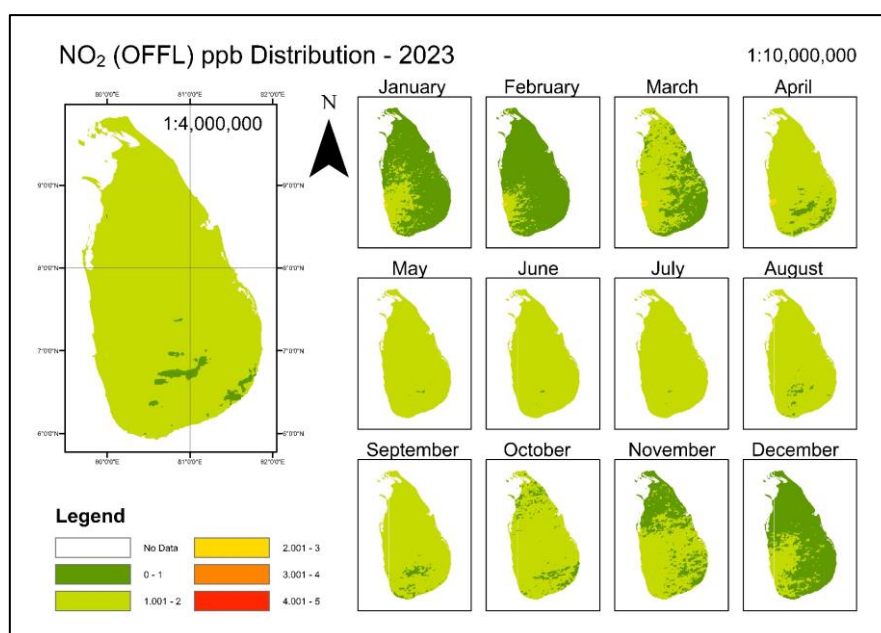


Fig. 12 Monthly Nitrogen Dioxide (NO₂) concentration maps for Sri Lanka in 2023, based on Sentinel-5P
Offline (OFFL) Level-3 satellite observations

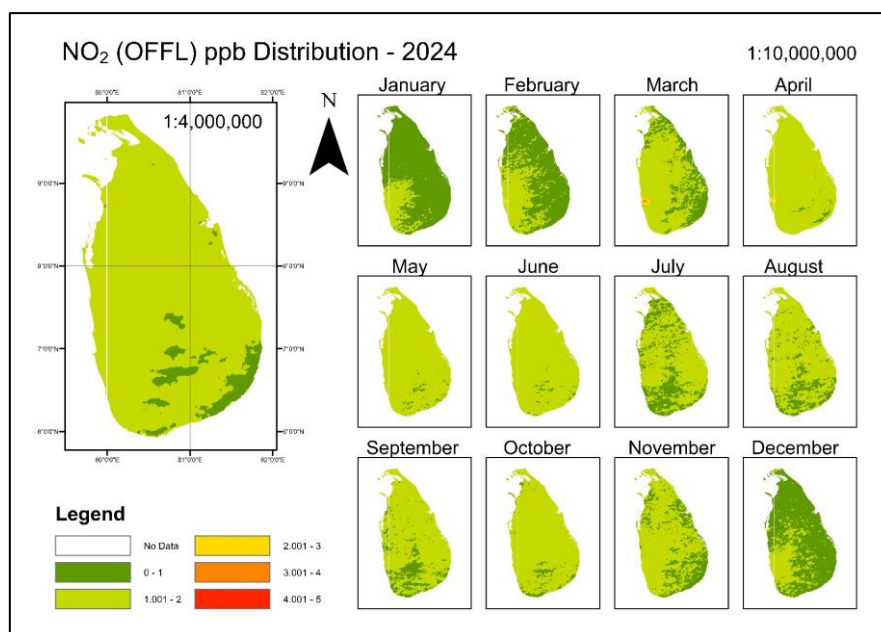


Fig. 13 Monthly Nitrogen Dioxide (NO₂) concentration maps for Sri Lanka in 2024, based on Sentinel-5P
Offline (OFFL) Level-3 satellite observations

3.2 Seasonal Variation and Meteorological Influence at NO₂

During the dry season (January–April), NO₂ levels were consistently higher in urban areas, with lower wind speeds trapping pollutants near the ground. The western coastal belt, particularly Colombo, recorded the highest concentration category (4–5 ppb) in March 2019 and 2020.

The southwest monsoon (May–September) caused noticeable NO₂ decreases across all districts. From June to August, concentrations across most districts fell into the lowest two categories (below 2 ppb), consistent with research linking rainfall and wind patterns to pollutant dispersion.

The northeast monsoon (December–February) had variable effects. Northern and eastern coastal districts showed slight NO₂ increases due to drier inland winds, while western districts (Gampaha, Colombo) maintained moderate levels from sustained human activities.

3.3 Impact of COVID-19 (2020–2021) in NO₂

A significant trend emerged in 2020 during the COVID-19 pandemic. Government movement restrictions and reduced industrial activity greatly affected NO₂ emissions. April–May 2020 maps showed marked NO₂ decreases in urban areas: Colombo and Kalutara, which recorded the highest concentration category (>4 ppb) in early 2019, fell to the lowest category (below 1 ppb) in the same months of 2020.

The decrease was short-lived. As lockdowns lifted in September 2020, NO₂ levels rose again, particularly in urban areas. This trend demonstrates the clear connection between human activity, economic output, and atmospheric NO₂ levels.

3.4 SO₂ Distribution Patterns

Sentinel-5P SO₂ data revealed distinct spatial patterns (Figs. 14–25). Unlike NO₂, which follows urban road networks and population centers, SO₂ hotspots concentrated around industrial activities. Puttalam (thermal power plants) and Kalutara (industrial zones) consistently showed high SO₂ concentrations across all study years.

SO₂ levels peaked during cooler months (November–February), coinciding with increased electricity demand and industrial heating. Coastal western and southern districts showed elevated levels, driven by port emissions and shipping activities near Colombo and Galle.

SO₂ concentrations generally remained lower than NO₂ (0–2 ppb) but exhibited concentrated spatial footprints indicating point-source rather than dispersed emissions. Maps demonstrated SO₂ remained localized but significant near power generation and industrial facilities.

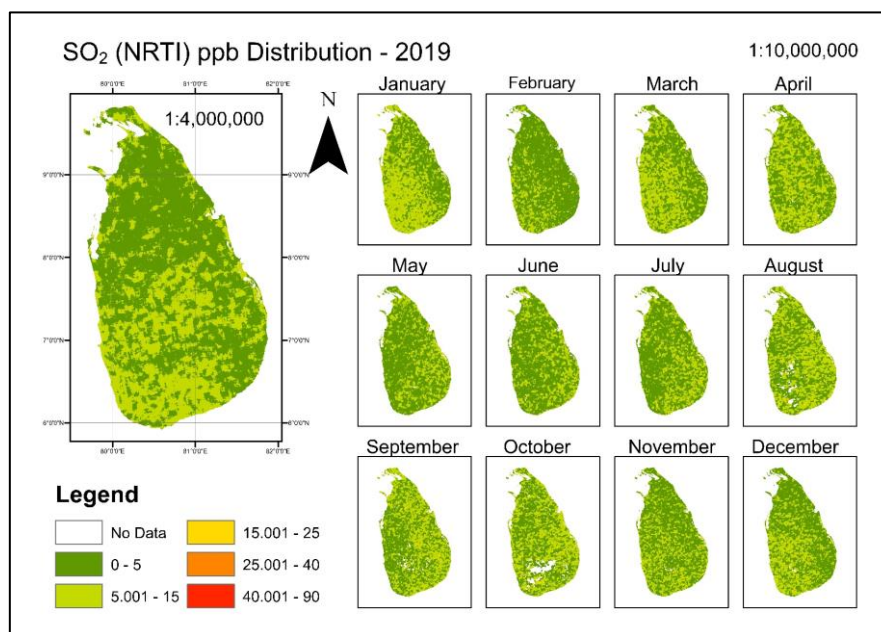


Fig. 14 Monthly Sulfur Dioxide (SO₂) concentration maps for Sri Lanka in 2019, based on Sentinel-5P Near Real-Time (NRTI) Level-3 satellite observations

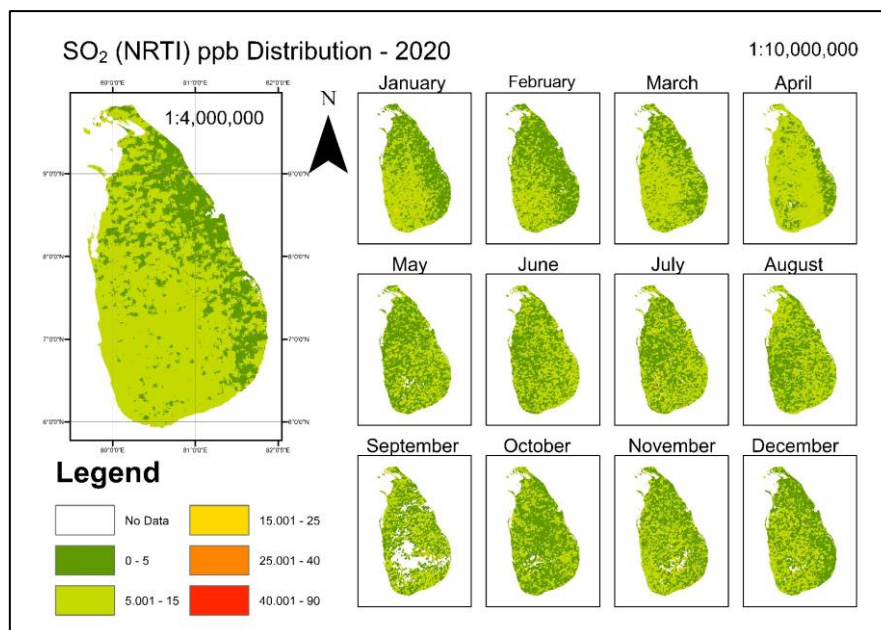


Fig. 15 Monthly Sulfur Dioxide (SO₂) concentration maps for Sri Lanka in 2020, based on Sentinel-5P Near Real-Time (NRTI) Level-3 satellite observations

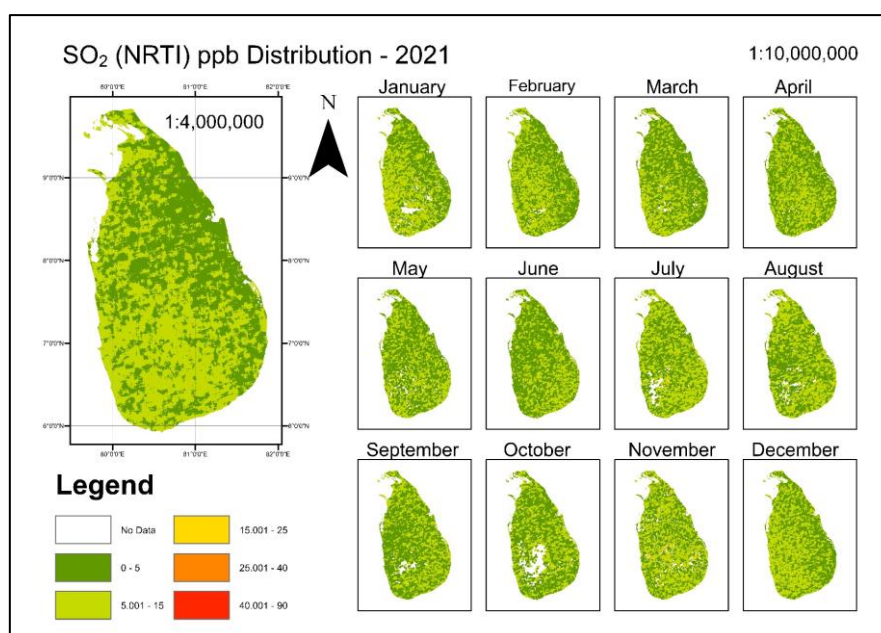


Fig. 16 Monthly Sulfur Dioxide (SO₂) concentration maps for Sri Lanka in 2021, based on Sentinel-5P Near Real-Time (NRTI) Level-3 satellite observations

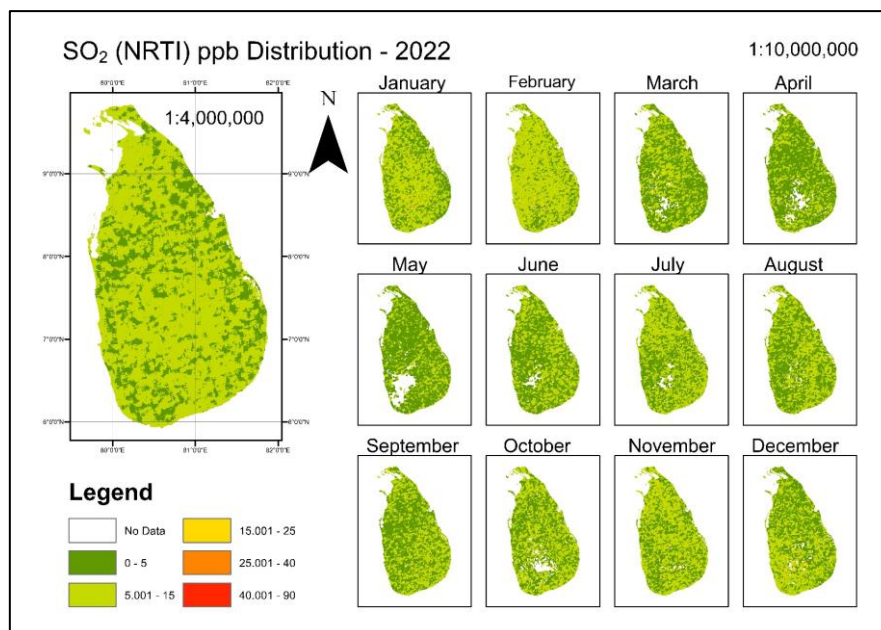


Fig. 17 Monthly Sulfur Dioxide (SO₂) concentration maps for Sri Lanka in 2022, based on Sentinel-5P Near Real-Time (NRTI) Level-3 satellite observations

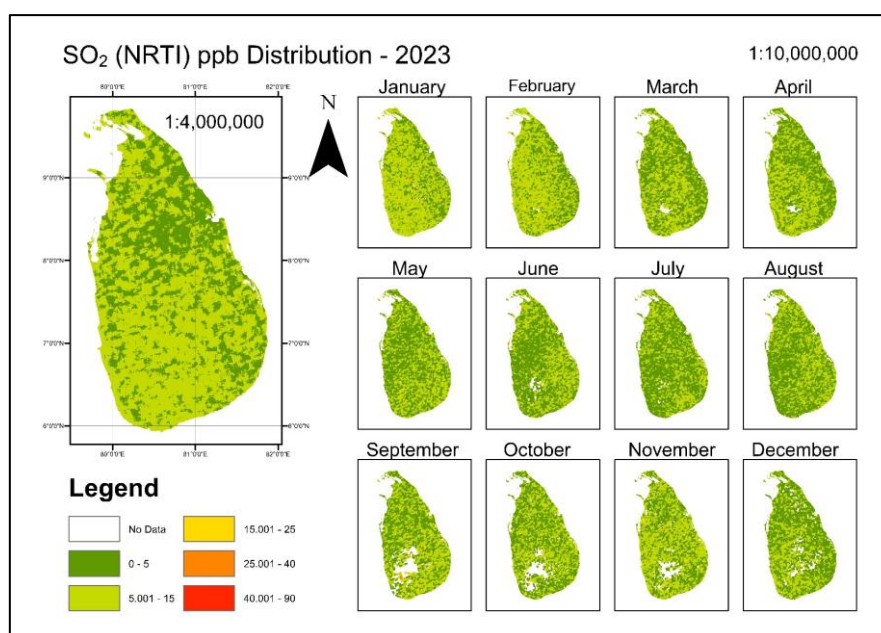


Fig. 18 Monthly Sulfur Dioxide (SO₂) concentration maps for Sri Lanka in 2023, based on Sentinel-5P Near Real-Time (NRTI) Level-3 satellite observations

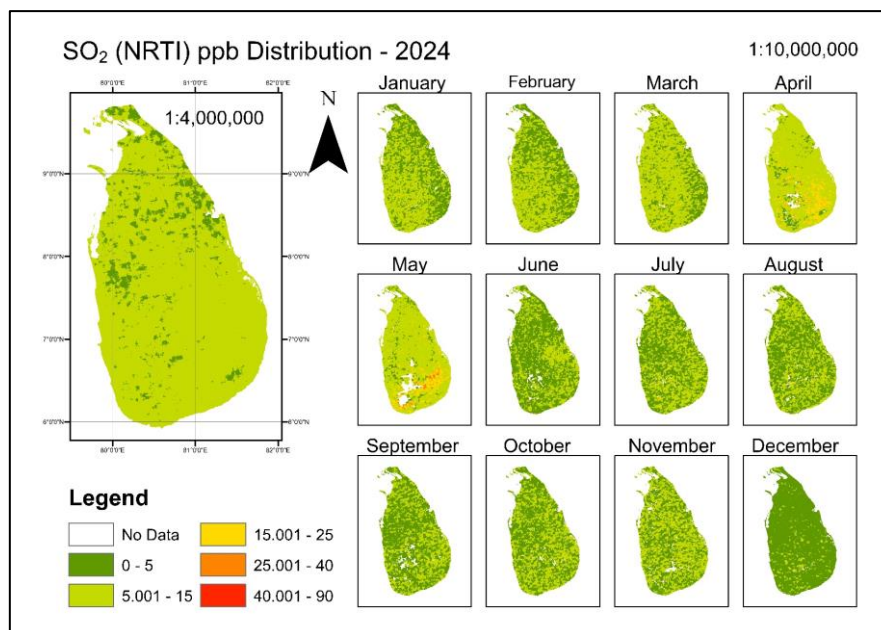


Fig. 19 Monthly Sulfur Dioxide (SO_2) concentration maps for Sri Lanka in 2024, based on Sentinel-5P Near Real-Time (NRTI) Level-3 satellite observations

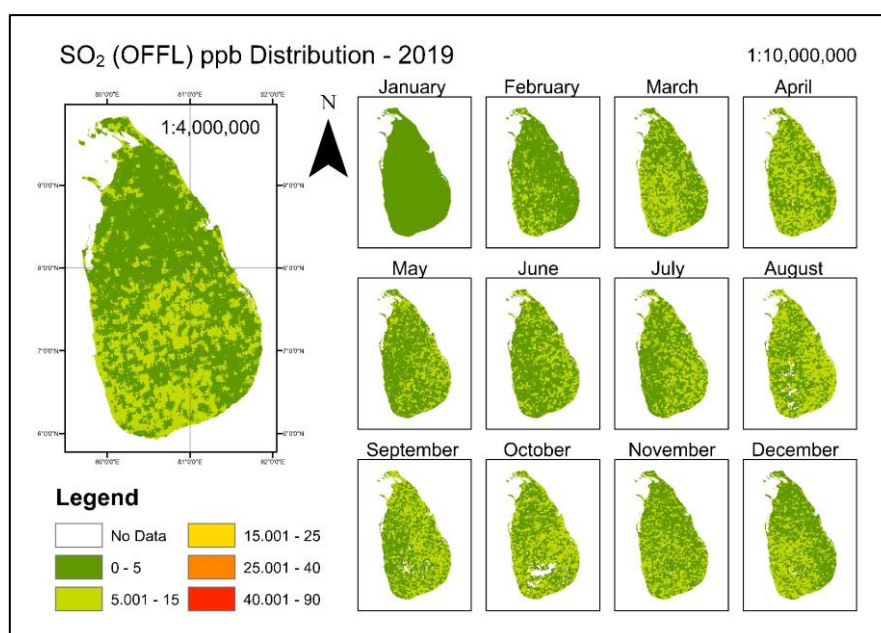


Fig. 20 Monthly Sulfur Dioxide (SO_2) concentration maps for Sri Lanka in 2019, based on Sentinel-5P Offline (OFFL) Level-3 satellite observations

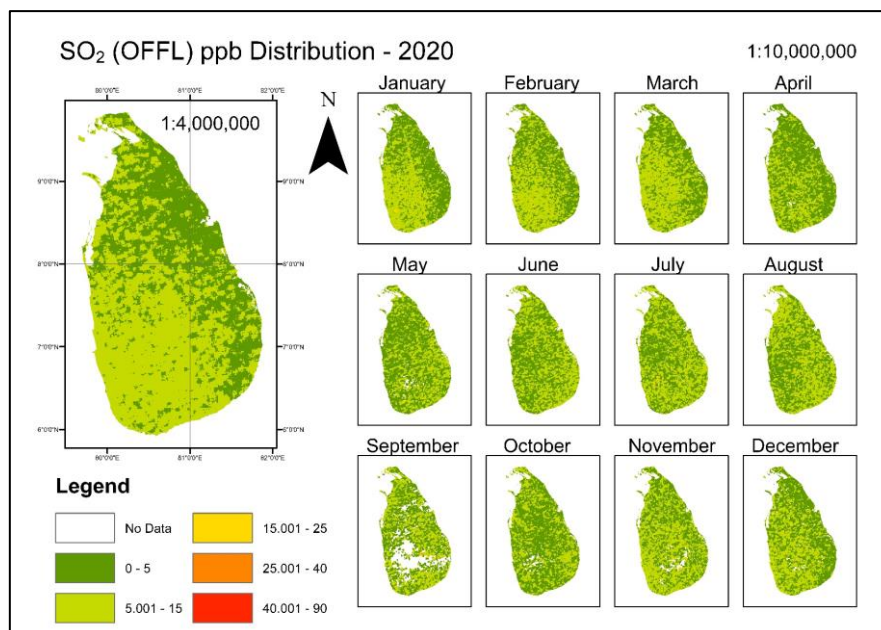


Fig. 21 Monthly Sulfur Dioxide (SO₂) concentration maps for Sri Lanka in 2020, based on Sentinel-5P Offline (OFFL) Level-3 satellite observations

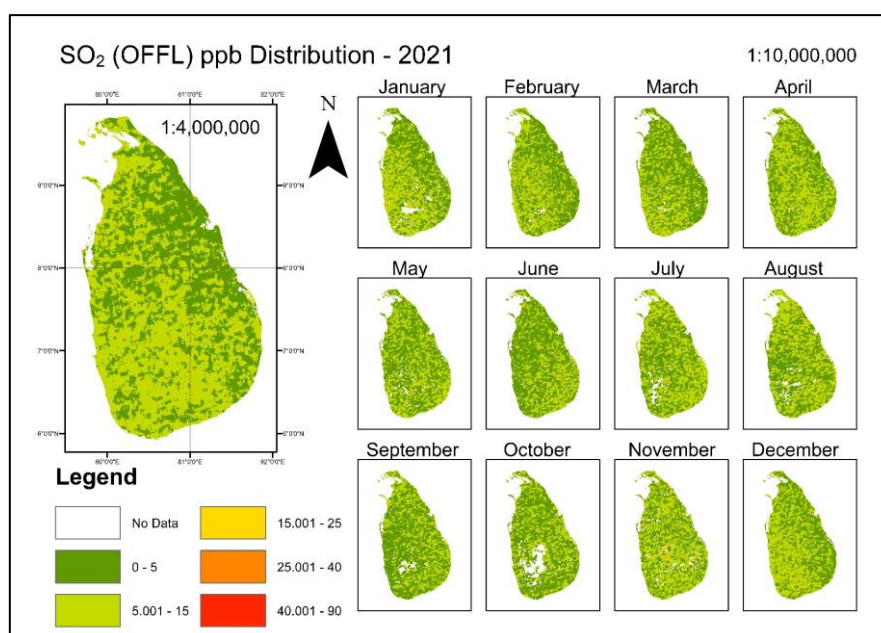


Fig. 22 Monthly Sulfur Dioxide (SO₂) concentration maps for Sri Lanka in 2021, based on Sentinel-5P Offline (OFFL) Level-3 satellite observations

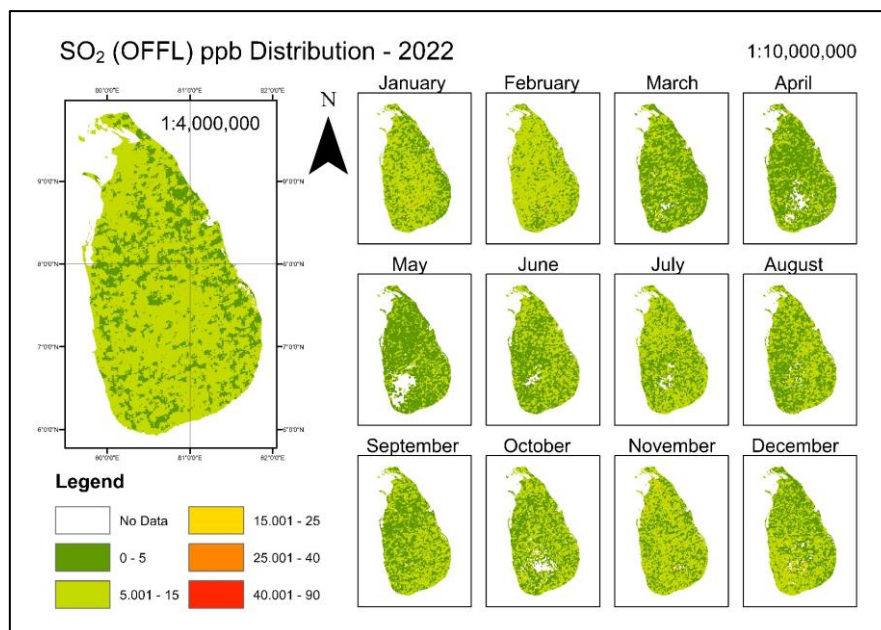


Fig. 23 Monthly Sulfur Dioxide (SO₂) concentration maps for Sri Lanka in 2022, based on Sentinel-5P Offline (OFFL) Level-3 satellite observations

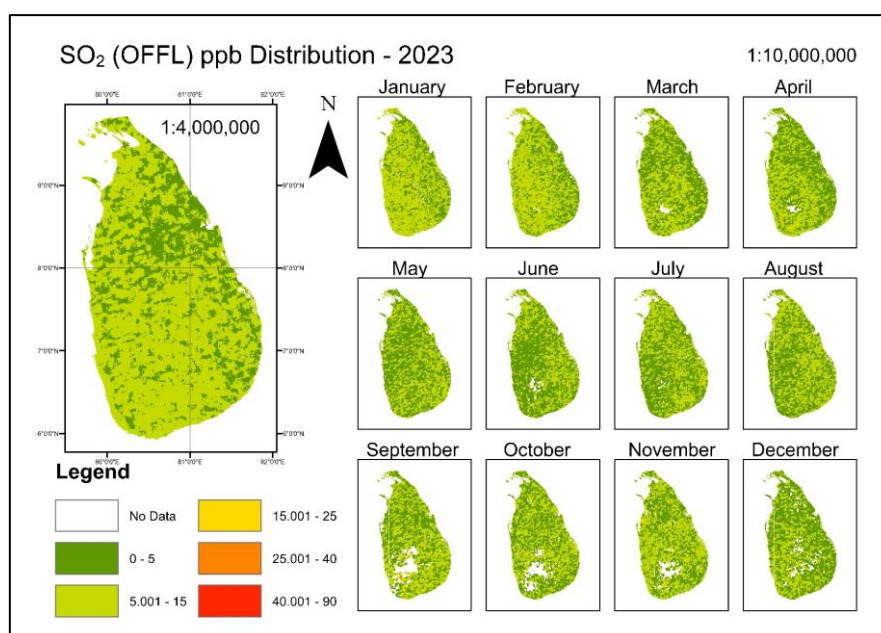


Fig. 24 Monthly Sulfur Dioxide (SO₂) concentration maps for Sri Lanka in 2023, based on Sentinel-5P Offline (OFFL) Level-3 satellite observations

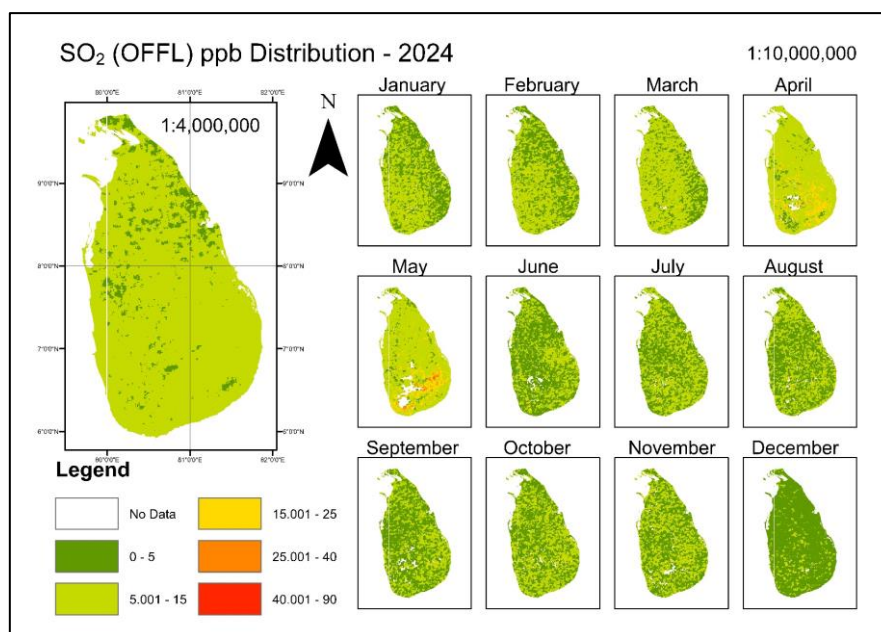


Fig. 25 Monthly Sulfur Dioxide (SO₂) concentration maps for Sri Lanka in 2024, based on Sentinel-5P Offline (OFFL) Level-3 satellite observations

3.5 Long-Term Trends (2019–2024) in SO₂

Over six years, urban NO₂ levels showed modest increases despite temporary COVID-19 lockdown decreases. Maps from 2023–2024 revealed slow increases near Colombo, Gampaha, Negombo, and Kurunegala, suggesting higher vehicle emissions, urban expansion, or ineffective emission reduction efforts.

SO₂ levels remained relatively stable but showed growing concentrations in Kalutara and Puttalam, indicating either rising industrial emissions or reduced atmospheric cleansing capacity.

Analysis revealed small dry-season pollutant increases in central highlands (Kandy, Nuwara Eliya), suggesting topographic influences on pollutant accumulation in valleys and elevated basins.

3.6 Hotspot Identification for NO₂ and SO₂

These western-region districts are characterised by heavy traffic, high energy consumption, and industrial clusters — a combination of drivers that, as discussed in Section 4, mirrors the corridor-level hotspots reported in other rapidly urbanising South and Southeast Asian regions, and that points to vehicle-emission control and industrial-zone management as priority mitigation measures.

SO₂ hotspots remained concentrated in the western coastal districts of Puttalam and Kalutara, consistently occupying the highest concentration categories during cooler, drier seasons. Unlike NO₂, SO₂ showed minimal seasonal variation and remained tied to specific point-source emissions rather than dispersed urban activity.

These visual hotspots enable targeted emission reduction strategies, including emissions zoning, real-time monitoring near thermal plants, and congestion pricing in urban areas (Carmona et al., 2021).

3.7 Comparison Between NRTI and OFFL Datasets

Both the NRTI and OFFL datasets were converted into monthly maps, but slight differences emerged in spatial smoothness and detection accuracy. The NRTI data offered quicker access but occasionally displayed pixel-level noise, particularly during months with heavy cloud cover. OFFL products provided clearer gradients and fewer irregularities, making them more dependable for long-term trend analysis and annual comparisons, while NRTI remained useful for quickly visualising short-term events such as lockdowns or seasonal increases (Vîrghileanu et al., 2020).

4. Discussion

The elevated NO₂ concentrations recorded in the Colombo–Gampaha–Kalutara corridor are consistent with patterns reported in other South Asian urban centres, where high traffic density, energy consumption, and industrial clustering combine to sustain persistently elevated NO₂ levels; comparable corridor-level hotspots have been documented around Mumbai (Kumar et al., 2016) and other rapidly urbanising South Asian cities using Sentinel-5P and related satellite products (Al-Alola et al., 2022; Wang et al., 2022). This convergence across studies conducted with different sensors and in different national contexts strengthens the interpretation that traffic and industrial density, rather than any Sri Lanka-specific factor, are the principal drivers of the western coastal NO₂ hotspot, and points to vehicle-emission control and industrial-zone management as the interventions most likely to yield measurable reductions.

The marked decline in NO₂ during the 2020 COVID-19 movement restrictions provides further, independent support for this interpretation. A similar reduction in NO₂ and SO₂ during COVID-19 lockdown periods was reported for Dhaka, Bangladesh, using a Google Earth Engine-based Sentinel-5P analysis, where restrictions on traffic and industrial activity produced comparable short-term pollutant declines followed by a rebound once restrictions eased (Hossin et al., 2025). The consistency of this lockdown signal across two South Asian megacity regions, despite differences in baseline pollution levels and urban structure, reinforces the conclusion that

anthropogenic activity, rather than meteorology alone, is the dominant driver of short-term NO₂ variability observed in this study.

SO₂ concentrations in this study remained consistently lower than NO₂, generally in the 0–2 ppb range. Compared against the World Health Organization's 2021 24-hour air-quality guideline for SO₂ (approximately 15 ppb) and Sri Lanka's national ambient air-quality standards (Central Environmental Authority, 2023), the SO₂ levels observed here are well within recommended limits at the spatial resolution examined, suggesting that current SO₂ emissions, while spatially concentrated around Puttalam and Kalutara, do not yet represent a widespread population-level exposure risk at the district scale. Localised, near-source exposure close to thermal power and industrial facilities cannot, however, be ruled out from column-averaged satellite data alone and would require ground-level verification.

Several limitations affect the interpretation of these results and warrant explicit discussion, together with recommendations for addressing them in future work. First, Sentinel-5P retrievals represent total atmospheric column densities rather than direct ground-level concentrations (Wang et al., 2022); the ppb conversion applied here (Section 2.3) assumes a fixed boundary-layer height and a well-mixed vertical column, which introduces additional uncertainty in areas of complex terrain such as the central highlands (Nuwara Eliya, Badulla), where boundary-layer height varies more strongly with elevation; future studies should incorporate site-specific or seasonally varying boundary-layer estimates, for example from reanalysis products, to reduce this source of error. Second, validation against ground-based measurements in this study was limited to the CEA stations at Battaramulla and Kandy; expanding the ground-monitoring network, or incorporating low-cost sensor networks, would allow more rigorous validation across a wider range of districts and terrain types. Third, this study relied on visual inspection of monthly raster composites to identify hotspots and seasonal patterns rather than on formal statistical trend analysis; future work should apply quantitative trend-detection methods such as the Mann-Kendall test with Sen's slope estimator, together with uncertainty and significance assessment, to substantiate the spatial and temporal patterns reported here. Fourth, cloud interference and limited satellite revisit frequency produced occasional gaps in monthly coverage, particularly in the central highlands during the monsoon; although monthly composites were used to mitigate this, some short-lived pollution events may not be fully captured. Finally, this study did not attempt to attribute observed concentrations to specific emission sources (traffic, industry, or biomass burning), account for secondary pollutant formation such as particulate matter (PM_{2.5}) that may co-vary with NO₂ and SO₂, or distinguish local emissions from possible transboundary transport, for example from southern India;

addressing these questions would require the integration of emission inventories, chemical transport modelling, and back-trajectory or wind-field analysis in future research.

Despite these limitations, the six-year, island-wide dataset developed here demonstrates that a satellite-and-GIS-based approach is a practical, low-cost complement to Sri Lanka's sparse ground-monitoring network, and provides a spatial and temporal baseline against which future, more rigorously validated studies can be compared.

5. Conclusions and Recommendations

5.1 Policy and Planning Implications

This study provides spatial-temporal insights for developing specialized air quality management strategies in Sri Lanka. Persistent NO₂ hotspots in urban areas highlight urgent need for emission reduction, particularly in transportation and construction. Colombo, Gampaha, and Kalutara could benefit from promoting electric vehicles, establishing low-emission zones, and enforcing stricter vehicle emission standards.

SO₂ reduction efforts should target industrial and power generation facilities. Continuous emissions monitoring systems in large factories and thermal plants (Puttalam, Kalutara) paired with stricter Environmental Protection License (EPL) enforcement and cleaner production incentives can reduce long-term SO₂ levels.

Integrating seasonal air quality forecasts into urban planning and public health recommendations can minimise population exposure. Pollution warnings and modified school schedules during high-pollution months protect vulnerable groups, particularly children and the elderly.

5.2 Recommendations for Future Research

This study has shown how effectively Sentinel-5P data can be used to evaluate air quality in a data-sparse setting, but several opportunities for further research remain. Building on the limitations discussed above (Section 4), expanding the ground-based validation network beyond Kandy and Battaramulla, potentially incorporating low-cost sensor networks, would strengthen confidence in satellite-derived estimates across a wider range of terrain and land-use types. Extending the analysis to other criteria pollutants, including particulate matter (PM_{2.5}), ozone (O₃), and carbon monoxide (CO), would provide a more complete picture of national air quality. Linking pollutant concentration data with population density, health records, and hospital admission data would allow the health burden associated with observed exposure patterns to be quantified. Incorporating advanced forecasting approaches, such as SARIMA time-series models or machine-learning methods including Random Forests and

Long Short-Term Memory (LSTM) networks, alongside meteorological and land-use variables, could improve the predictive accuracy of future air-quality assessments. Finally, the anomalous readings observed in some northern and eastern districts, despite low local emissions, point to a need for dedicated transboundary pollution studies using wind back-trajectory modelling and regional emission scenarios to assess the potential contribution of long-range transport, including from southern India.

5.3 Practical Use of Map-Based Outputs

This study's visual communication is one of its main strengths. The monthly map panels provide a clear way to understand how air pollution changes over the year and varies by region. Environmental authorities, urban planners, educators, and policymakers can use these outputs to increase awareness and guide their decisions (Meltus & Karanja, 2024).

Environmental Protection Agencies can utilise these maps to identify which districts should be prioritized for the placement of monitoring stations or for enforcing regulations. Urban planners can utilise trends over time to inform their decisions about zoning and infrastructure development, particularly concerning highways, ports, and industrial parks. In public communication, easier-to-understand versions of these maps can be shared on social media or included in mobile apps to help keep everyone updated on current or predicted pollution levels.

Additionally, standardising the maps with fixed legends and consistent classifications makes it easier to compare data from year to year. This provides a clear record of changes in air quality that can help assess the effectiveness of policy actions or development initiatives.

5.4 Conclusion

This study demonstrates that freely available Sentinel-5P satellite data, combined with GIS, can characterise the spatial and temporal dynamics of NO₂ and SO₂ across a data-sparse developing country such as Sri Lanka. Over six years, the western coastal corridor emerged as a persistent NO₂ hotspot linked to urbanisation and traffic, while SO₂ remained concentrated around industrial and power-generation sources in Puttalam and Kalutara, with both pollutants showing clear monsoon-driven seasonality and a marked, if temporary, decline during the 2020 COVID-19 restrictions.

The complementary strengths of the NRTI and OFFL products, demonstrated here for near-real-time and long-term applications respectively, together with the ground-validation and quantitative trend-analysis directions

outlined above, offer a practical and extensible framework for integrating satellite-based monitoring into national air-quality management in Sri Lanka and comparable settings.

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