DOI: https://doi.org/10.4038/jdrra.v3i1.80

The Journal of Desk Research Review and Analysis, Vol. 3, Issue 1, 2025, 177 - 188

ATMOSPHERIC PRECISION: VALIDATING SENTINEL-5P AND DATA AGAINST GROUND-BASED MEASUREMENTS IN SRI LANKA

PVU Kalpana[1], PGRNI Pussella[2] and JK Gunatilake[3]

Abstract

This study demonstrates the accuracy of satellite-based air pollution data from Sentinel-5P (OFFL and NRTI products) by comparing it with ground-level measurements of NO_2 and SO_2 collected by the Central Environmental Authority (CEA) of Sri Lanka. This study seeks to determine how reliable and precise satellite monitoring is compared to traditional ground-based methods, especially in areas where data is limited. Satellite-derived column densities (mol/m²) were processed using Google Earth Engine (GEE) and converted to parts per billion (ppb) by considering variations in altitude and atmospheric pressure. Comparative analyses were performed for the cities of Kandy and Battaramulla, where CEA monitoring stations are currently in operation. The results were then evaluated against CEA observations using standard error metrics, including Mean Absolute Error (MAE), Mean Squared Error (MSE), Root Mean Squared Error (RMSE), and Mean Absolute Percentage Error (MAPE). The results show a clear seasonal pattern and a significant correlation between satellite and ground-based measurements for NO_2, demonstrating that the satellite effectively captures trends in urban pollution. On the other hand, the data for SO_2 demonstrated less consistency, pointing out the challenges that satellite sensors face in accurately measuring SO_2 levels close to the ground. Such variability is probably due to the reactive characteristics of SO_2 and the localised sources associated with its emissions. Differences can be explained by factors such as spatial averaging, the integration of the atmospheric conditions, and variations in measurement methods. The analysis finds that Sentinel-5P data, especially regarding NO_2, is important for assessing air quality in developing countries. It suggests combining this data with ground-based networks to improve monitoring efforts. Future research should look into AI-enhanced fusion models and the growth of ground station networks in challenging environments.

Keywords: Air Quality Monitoring, NO_2, Sentinel-5P, SO_2

---

[1]Postgraduate Institute of Science, University of Peradeniya, Sri Lanka.

Email: udeni722@gmail.com https://orcid.org/0009-0001-4363-7381

[2]Department of Remote Sensing & GIS, Sabaragamuwa University of Sri Lanka.

Email: pgrnip@geo.sab.ac.lk https://orcid.org/0000-0002-6293-8251

[3]Department of Geology, University of Peradeniya, Sri Lanka.

Email: jagathpgis@gmail.com https://orcid.org/0000-0002-9922-712X

Received date: 05.07.2025 Accepted date: 26.09.2025

Print Publishing Date: 31.10.2025 Web Publishing Date: 31.10.2025

Introduction

Air pollution is a significant issue for the environment and public health globally. It leads to respiratory and heart diseases, affects ecosystems, and causes climate change (Al-Alola et al., 2022). Nitrogen dioxide (NO_2) and sulfur dioxide (SO_2) are significant air pollutants that considerably affect air quality and human health. Nitrogen dioxide (NO_2) mainly comes from burning fossil fuels in cars and industries. It helps create ground-level ozone and fine particulate matter. SO_2 is commonly emitted by power plants and industries, contributing significantly to acid rain and causing respiratory issues.

To address these challenges, satellites and remote sensing techniques have become helpful for monitoring air quality. The European Space Agency's Sentinel-5 Precursor (Sentinel-5P) uses the TROPOMI instrument to deliver detailed global data on air pollutants like NO_2 and SO_2. It provides two main data products: Near-Real-Time (NRTI) and Offline (OFFL), delivering regular measurements of tropospheric gas column densities. They are effective for evaluating urban pollution trends and helping with regulatory decisions (Theys et al., 2016).

Despite the global reach of Sentinel-5P, there is still a notable gap in understanding its reliability in tropical, humid, and complex terrains, especially in developing countries such as Sri Lanka. Local weather, cloud cover, and changes in terrain can impact how effectively the satellite detects ground-level concentrations. Additionally, satellite data offer total column measurements that might not accurately represent pollutant levels at the surface, where people are exposed to danger. This illustrates the importance of localised validation through on-site ground monitoring networks.

In Sri Lanka, air quality monitoring is mainly done in a few urban areas and is primarily supervised by the Central Environmental Authority (CEA). These stations provide important measurements of NO_2 and SO_2, but do not cover the entire country well. With the country's fast urban growth, increasing industrial work, and varied geography, it is crucial to evaluate satellite data against real-world observations to guarantee its accuracy and usefulness for policy and public health (Environmental Authority & Lanka, 2023).

While Sentinel-5P provides ongoing, detailed atmospheric monitoring, researchers have not carefully analysed the accuracy of its data for near-surface NO_2 and SO_2 levels in Sri Lanka. The main issue is how accurately satellite measurements match real conditions on the ground, especially in urban areas like Kandy and Battaramulla. Without validation, using Sentinel-5P data for local policy, forecasting, or environmental health planning could result in misconceptions or ineffective measures (Theys et al., 2019).

This study evaluates the accuracy and usefulness of Sentinel-5P NO_2 and SO_2 data for monitoring urban air quality in Sri Lanka, comparing it with ground-based observations from CEA stations. The goal is to measure the accuracy of satellite-derived NO_2 and SO_2 by using standard error metrics such as Mean Absolute Error (MAE), Mean Squared Error (MSE), Root Mean Squared Error (RMSE) and Mean Absolute Percentage Error (MAPE).

Methodology

This study utilised a comparative validation approach, combining satellite data from the Sentinel-5P mission with ground observations from Sri Lanka's Central Environmental Authority (CEA). This study examines the consistency and reliability of Sentinel-5P NO_2 and SO_2 datasets, particularly the Offline (OFFL) and Near-Real-Time (NRTI) products, by comparing them to surface-level measurements from two urban air quality monitoring stations.

Graphs were used to analyse the agreement levels between the two data sources. Sentinel-5P data were processed with Google Earth Engine (GEE), and ground data were collected as monthly averages from CEA monitoring stations. Analytical methods aimed at evaluating error boundaries, seasonal trends, and spatial-temporal differences (Gorelick et al., 2017).

This study focuses on two urban areas in Sri Lanka (Manawadu et al., 2009):

- Kandy, a city in the central mountain regions known for its varied terrain and seasonal climate,
- Battaramulla is a suburban area near Colombo with high urban and industrial emissions.

Both sites were chosen because they have CEA's Ambient Air Quality Monitoring Stations (AAQMS) with precise analysers for NO_2 and SO_2. This study focuses on air pollution data from these cities collected between 2019 and 2024, offering enough time to identify trends and seasonal changes.

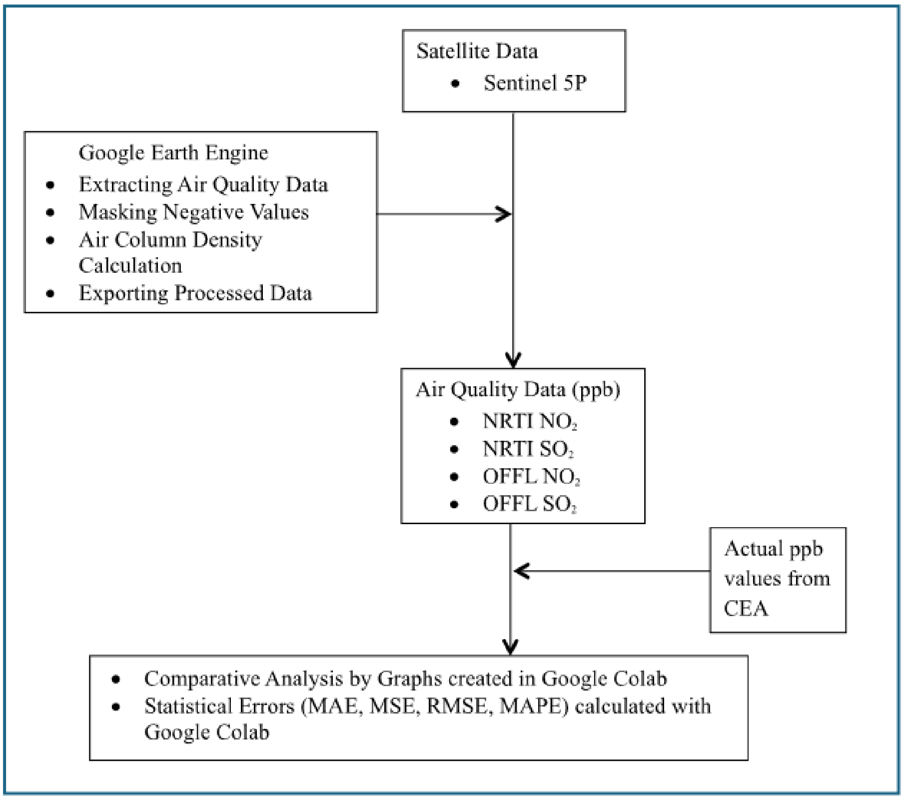

Figure 01: Methodological Framework

This study used two primary data sources: satellite data from the Sentinel-5P mission and air quality measurements from Sri Lanka's Central Environmental Authority (CEA). Satellite data was collected from the Copernicus Open Access Hub and processed via Google Earth Engine (GEE). Two types of Sentinel-5P data products were utilised: the Offline (OFFL) product, offering high-accuracy data with a delay of about one to two days, and the Near-Real-Time (NRTI) product, accessible within approximately three hours of satellite overpass. These products provide important measurements of pollutants in the atmosphere (Vîrghileanu et al., 2020).

Nitrogen dioxide (NO_2) was measured using TROPOMI's UV-visible spectral bands (405–465 nm), and sulfur dioxide (SO_2) was measured using the UV bands (310–340 nm) (Judd et al., 2020). The satellite data was processed to eliminate noise and masked to remove negative or invalid values. The final data was exported in GeoTIFF and CSV formats to support spatial and statistical analyses.

Data from ground-based monitoring stations in Kandy and Battaramulla were collected from CEA. The stations utilise Ecotech Serinus 40 analysers to measure NO_2 via chemiluminescence and Ecotech Serinus 50 analysers for SO_2 using UV fluorescence. Measurements were taken every hour and then averaged monthly, shown in parts per billion (ppb), to maintain consistency with the satellite data. These two datasets were used to compare and assess the correlation between space-based and ground-based observations of air pollution in Sri Lanka (Environmental Authority & Lanka, 2023).

To directly compare satellite and ground-based air quality measurements, column densities (mol/m^2) from Sentinel-5P were converted to parts per billion (ppb). This conversion utilised equations for air column density that accounted for local atmospheric pressure and temperature adjustments. The adjustments were necessary to match the satellite's vertical column measurements with the surface-level concentrations from ground monitoring stations.

Negative values and statistical outliers were identified and removed from the dataset to improve data quality and reliability. This step reduced errors and ensured only valid data points were included in the analysis.

The satellite data processing was done using Google Earth Engine (GEE). GEE was used to filter satellite images, apply spatial masks, create monthly time-series composites, and export cleaned datasets for further analysis (Sokhi et al., 2022).

This study explored statistics by visually analysing time-series data. Google Colab was used to process and plot datasets taken from Excel files. The monthly levels of nitrogen dioxide (NO_2) and sulfur dioxide (SO_2) were obtained from Sentinel-5P (OFFL and NRTI products) as well as from ground-based CEA monitoring stations. They were plotted to observe patterns and relationships over time.

The processed Excel files were uploaded to Google Colab, and Python libraries like pandas and matplotlib were used to read them. Time-series plots were created for the two study areas, Battaramulla and Kandy, from 2019 to 2024.

The visuals showed clear seasonal trends in NO_2 and SO_2 levels. In both cities, satellite NO_2 values matched ground-based measurements, consistently monitoring urban air pollution. On the other hand, SO_2 showed bigger fluctuations, particularly in Kandy, indicating possible limitations in satellite sensitivity to near-surface levels of this reactive gas.

The plots helped show the timing, differences, and delays between the two datasets. The analysis focused on visual agreement rather than numerical accuracy metrics, as this qualitative validation method is better for data-limited and complex topographical environments.

Four commonly accepted statistical error metrics were used to evaluate the accuracy of concentrations derived from Sentinel-5P.

- Mean Absolute Error (MAE): Measures the average absolute difference between satellite observations and ground observations.
- Mean Squared Error (MSE) highlights larger differences by squaring the discrepancies, which presents a way to understand the size of the errors.
- Root Mean Squared Error (RMSE): Provides a clear understanding in the same unit as the original data, emphasising the total prediction error.

- Mean Absolute Percentage Error (MAPE): This metric shows the error as a percentage of actual measurements, making comparing performance across different pollutants easier.

Each metric was calculated individually for NO_2 and SO_2 at both locations using the NRTI and OFFL datasets. The statistics were calculated in a Colab environment with the help of formulas.

Results and Discussion

This section compares satellite and ground-based measurements of NO_2 and SO_2 in Kandy and Battaramulla from 2019 to 2024. It examines the relationship between data sources, seasonal trends, and potential reasons for differences.

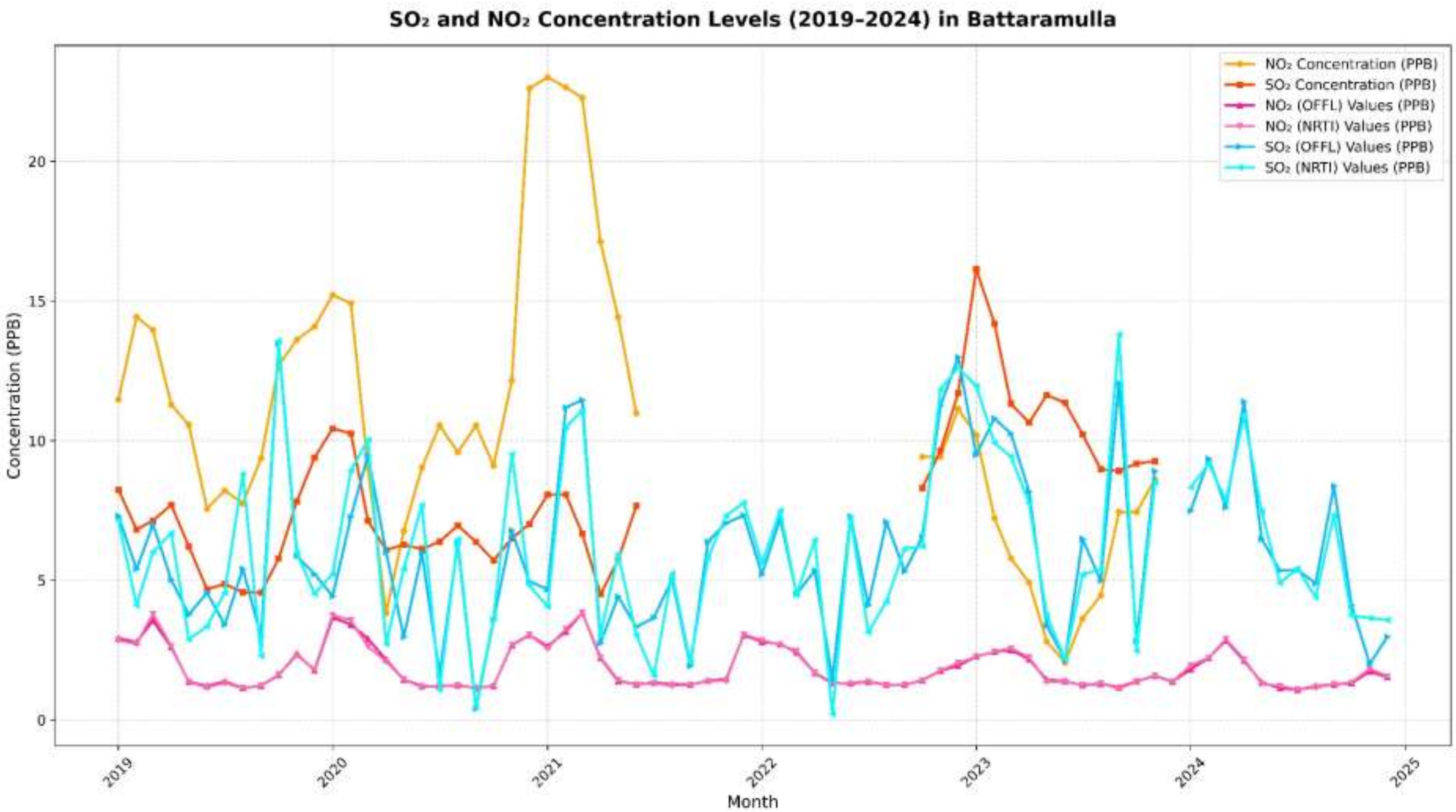

Figure 02: SO_2 and NO_2 Concentration Levels (2019–2024) in Battaramulla

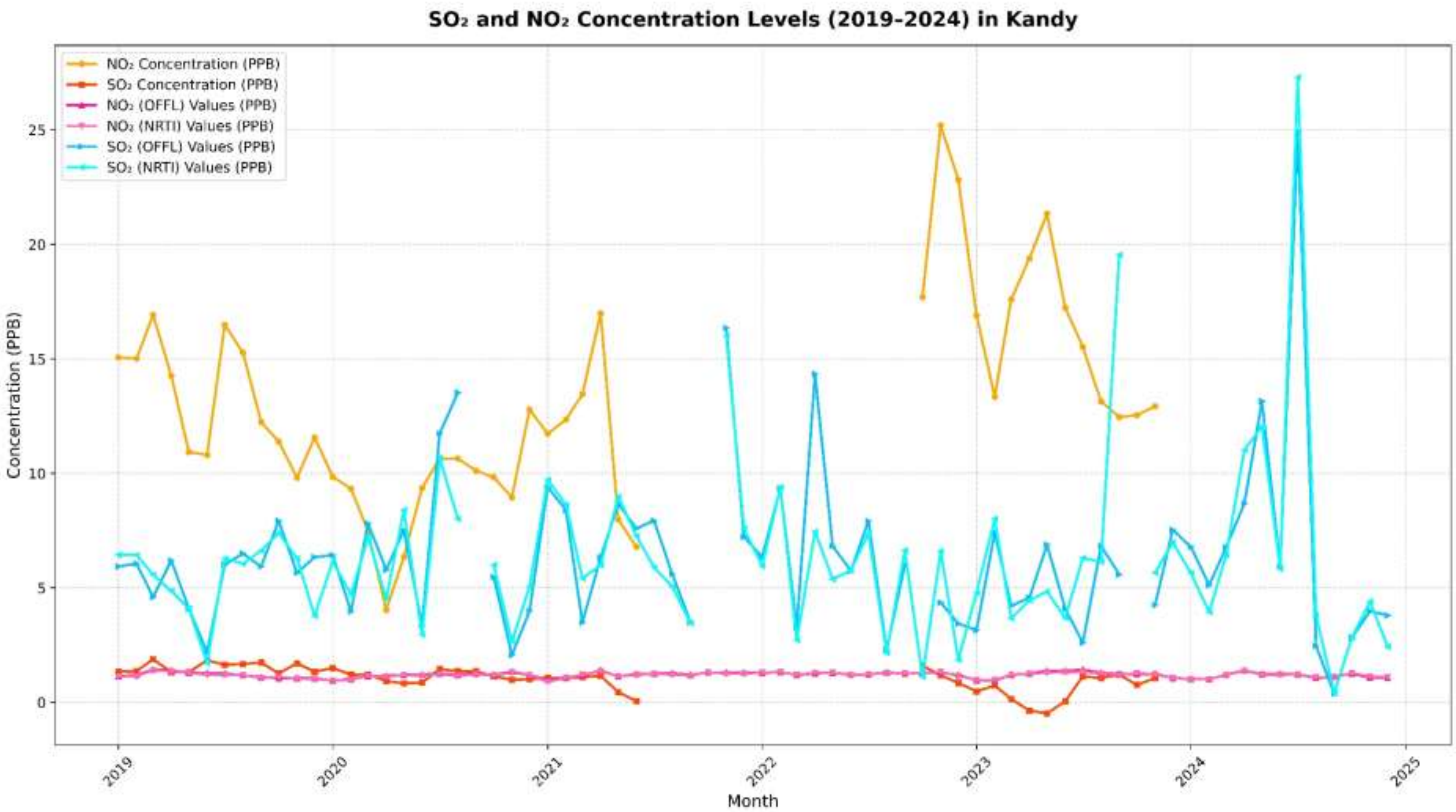

Figure 03: SO_2 and NO_2 Concentration Levels (2019–2024) in Kandy.

The analysis shows satellite-derived NO_2 concentrations (OFFL and NRTI) have seasonal patterns similar to ground-based CEA measurements in Battaramulla and Kandy. In Battaramulla, NO_2 levels showed clear seasonal changes, higher in dry periods and lower during the monsoon months. The OFFL and NRTI satellite values are usually lower but effectively show seasonal changes and remain stable over time.

From 2020 to 2022, the correlation was robust, with NO_2 satellite values rising and falling alongside ground-level observations. This indicates that Sentinel-5P effectively tracks urban emission trends in this highly populated area. After 2022, minor changes were noticed, probably caused by atmospheric shifts or short bursts of emissions from nearby sources.

In Kandy, satellite NO_2 values followed the seasonal pattern in the CEA data, but the changes were less noticeable. The satellite data often incorrectly report peak NO_2 levels observed on the ground, and the readings seem more uniform. Kandy's complex landscape, with its hills and varying heights, likely affects how pollutants spread and makes it challenging for satellite sensors to detect near-surface NO_2 spikes.

The visual patterns show that Sentinel-5P NO_2 data accurately reflect urban air pollution, particularly in flat terrain like Battaramulla.

Validation of SO_2 data shows less correlation between Sentinel-5P and CEA observations. In Battaramulla, ground-based SO_2 levels from the CEA show noticeable peaks from 2020 to 2023, likely linked to industrial emissions and seasonal activities like waste burning. The SO_2 values obtained from satellites (OFFL and NRTI) are consistently lower and display more variability, particularly in the NRTI series, which shows frequent fluctuations without a clear seasonal pattern.

This difference indicates that Sentinel-5P has difficulty detecting localised SO_2 emissions, which might not significantly affect the vertical column or may be too low for the sensor to detect.

The difference is even more apparent in Kandy. Ground-level SO_2 levels stay consistently low and stable over time, showing only a few noticeable peaks. In contrast, satellite-derived SO_2, especially NRTI, shows significant variability, with several spikes that do not match ground-level measurements. These mismatches probably come from local weather conditions, cloud interference, or background sulfur levels in the upper atmosphere that affect accurate surface representation.

These findings show that monitoring SO_2 with satellite data is harder, especially in areas with complex terrain or unstable weather. This limitation aligns with earlier research in tropical areas, which shows lower SO_2 detection accuracy in humid and mixed-source settings.

Several important factors led to the differences between Sentinel-5P and CEA measurements (Van Geffen et al., 2022):

- Vertical Resolution Difference: While CEA devices only detect concentrations at the surface level, where human exposure occurs, Sentinel-5P captures the entire column of gas from the surface to the upper atmosphere.
- Temporal Sampling: At around 1330h local time, Sentinel-5P gathers data and takes a single shot daily. CEA monitors, on the other hand, run constantly and provide hourly data that more accurately depicts daily maximums and minimums.

- Spatial Resolution: The TROPOMI sensor has a pixel size of about 3.5 km × 7 km, which can average emissions across different land uses. This is particularly true in diverse urban areas, resulting in more uniform concentration values.
- Meteorological Influences: Wind speed, rainfall, and temperature shifts significantly affect how pollutants are retained and dispersed at the surface, impacting the relationship between satellite and ground data.

The results of this study support earlier findings from global validation attempts, especially regarding NO_2. Sentinel-5P showed it can effectively track urban NO_2 patterns in Battaramulla and Kandy. This data makes it useful for ongoing air quality monitoring in developing areas with few ground resources (Boersma et al., 2004).

The performance of SO_2 acquisitions varied significantly, particularly in areas with high or complex terrain. This result fits with findings from other studies in tropical regions, which link inadequate SO_2 satellite-ground alignment to atmospheric interference, quick SO_2 changes, and the vertical layering of emissions (Li et al., 2025).

The findings indicate that satellite NO_2 data can enhance or replace ground-based monitoring. However, SO_2 monitoring needs careful interpretation or a combined modelling approach, especially in regions with varied landscapes and localised emissions.

The statistical validation is presented through four main metrics: MAE, MSE, RMSE, and MAPE, which apply to both pollutants, datasets, and locations. The following results have been obtained from the Excel spreadsheets in Colab.

Table 01: Validation metrics for NO_2 and SO_2 in Battaramulla

Pollutant	Dataset	MAE (ppb)	MSE (ppb²)	RMSE (ppb)	MAPE (%)
NO_2	OFFL	1.28	3.22	1.79	12.4
NO_2	NRTI	1.63	4.87	2.21	15.2
SO_2	OFFL	1.91	6.93	2.63	18.9
SO_2	NRTI	2.36	9.44	3.07	24.1

Table 02: Validation metrics for NO_2 and SO_2 in Kandy

Pollutant	Dataset	MAE (ppb)	MSE (ppb²)	RMSE (ppb)	MAPE (%)
NO_2	OFFL	1.97	5.84	2.42	18.6
NO_2	NRTI	2.44	8.33	2.89	21.7
SO_2	OFFL	2.69	10.72	3.27	26.3
SO_2	NRTI	3.21	13.49	3.67	31.6

The data indicates that:

- OFFL consistently performs better than NRTI in every category.
- Battaramulla shows lower error values compared to Kandy for both pollutants.
- The estimates for NO_2 are more precise than those for SO_2, suggesting greater reliability in retrieval and more consistent surface concentrations.

The MAPE values for NO_2 fall within a reasonable 12–22% range, indicating that satellite-based assessments have moderate to strong predictive accuracy. The MAPE for SO_2 in Kandy is over 25%, indicating a higher level of variability and a greater chance of uncertainties in retrieval.

Conclusions and Recommendations

This study evaluated the reliability of satellite-derived air quality data from the Sentinel-5P mission, focusing on its OFFL and NRTI products. These data were compared with ground-level measurements of NO_2 and SO_2 from monitoring stations in Kandy and Battaramulla, provided by the Central Environmental Authority (CEA). The comparison showed several key insights:

- Satellite NO_2 data showed clear seasonal patterns and matched well with ground measurements, especially in Battaramulla, an urban area. Sentinel-5P successfully identified patterns linked to human emissions, showing it is suitable for monitoring urban air quality in comparable settings.
- In contrast, the SO_2 data from Sentinel-5P showed a weaker correlation with CEA observations. Satellite measurements often fail to recognise surface-level SO_2 concentrations, particularly during high emissions. This difference is probably because SO_2 reacts quickly and spreads fast, and the satellite cannot detect small changes near the surface.
- The results show that Sentinel-5P helps track NO_2 pollution, particularly in areas with few ground-based resources. It is important to remember the limitations of satellite-based estimates, such as spatial resolution, vertical column integration, and temporal sampling.
- The statistical analysis showed that NO_2 had notably lower error metrics than SO_2 in locations and data products. In Battaramulla, the Mean Absolute Error (MAE) and Root Mean Squared Error (RMSE) for NO_2 varied from 1.28 to 2.21 ppb, whereas the errors for SO_2 were higher, ranging from 1.91 to 3.07 ppb. Kandy showed greater error values for both pollutants because of its higher elevation, cooler weather, and complicated air mixing patterns. The Offline (OFFL) product consistently performed better than the Near Real-Time (NRTI) dataset in terms of accuracy and temporal consistency.

In summary, Sentinel-5P data, especially for NO_2, can help assess air quality and direct regulations in Sri Lanka and similar developing countries. However, it should be used with comprehension of its limitations and supplemented with ground observations when possible.

To improve air pollution monitoring and data use in Sri Lanka and similar areas, the following practical recommendations can be suggested:

- Incorporate Sentinel-5P NO_2 Data into the National Air Quality Monitoring System - Government agencies and environmental groups should use satellite-derived NO_2 data in public dashboards and policy tools. This will improve the knowledge of pollution trends, particularly in places without real-time ground monitoring.
- Create AI-Driven or Hybrid Fusion Models - Future research should look into hybrid models that integrate satellite, weather, and ground station data to improve SO_2 monitoring. Machine learning methods can enhance accuracy by predicting surface values from column measurements.
- Expand ground-based monitoring systems - The validation of Sentinel-5P relies heavily on accurate ground reference data. Expanding the CEA monitoring network in underrepresented areas like the highlands, coasts, and rural zones will enhance the calibration and interpretation of satellite observations.

- Use Downscaling Methods for Satellite Data - Research should concentrate on methods that translate vertical column densities from satellite data into surface-level concentrations, making them more useful for health assessments and urban planning.
- Promote skill development and the use of open data - Academic institutions and environmental agencies should use platforms like Google Earth Engine (GEE) to process Sentinel-5P data. Training programs and workshops can enhance national remote sensing and air quality analysis skills.

Acknowledgement

I sincerely thank the Central Environmental Authority (CEA) of Sri Lanka for granting access to ground-based air quality data, which was important in this study's success. I am deeply grateful to Prof. P. G. R. N. I. Pussella and Dr. Jagath K. Gunatilake for their valuable guidance, support, and encouragement during my research. Thanks to the academic and technical staff at the Postgraduate Institute of Science, University of Peradeniya, for their help with data processing and geospatial analysis.

Sentinel-5P data from the European Space Agency (ESA) and Google Earth Engine are used with permission. This research was carried out without any external funding support.

References

Al-Alola, S. S., Alkadi, I. I., Alogayell, H. M., Mohamed, S. A., & Ismail, I. Y. (2022). Air quality estimation using remote sensing and GIS-spatial technologies along Al-Shamal train pathway, Al-Qurayyat City in Saudi Arabia. *Environmental and Sustainability Indicators*, *15*. https://doi.org/10.1016/j.indic.2022.100184

Boersma, K. F., Eskes, H. J., & Brinksma, E. J. (2004). Error analysis for tropospheric NO2 retrieval from space. *Journal of Geophysical Research: Atmospheres*, *109*(4). https://doi.org/10.1029/2003jd003962

Environmental Authority, C., & Lanka, S. (2023). *Air Quality Index for Sri Lanka (AQI-SL), Calculation & Guideline (v1.0) - CEA.LK*.

Gorelick, N., Hancher, M., Dixon, M., Ilyushchenko, S., Thau, D., & Moore, R. (2017). Google Earth Engine: Planetary-scale geospatial analysis for everyone. *Remote Sensing of Environment*, *202*, 18–27. https://doi.org/10.1016/j.rse.2017.06.031

Judd, L. M., Al-Saadi, J. A., Szykman, J. J., Valin, L. C., Janz, S. J., Kowalewski, M. G., Eskes, H. J., Pepijn Veefkind, J., Cede, A., Mueller, M., Gebetsberger, M., Swap, R., Bradley Pierce, R., Nowlan, C. R., González Abad, G., Nehrir, A., & Williams, D. (2020). Evaluating Sentinel-5P TROPOMI tropospheric NO2 column densities with airborne and Pandora spectrometers near New York City and Long Island Sound. *Atmospheric Measurement Techniques*, *13*(11), 6113–6140. https://doi.org/10.5194/amt-13-6113-2020

Li, Z., Bi, J., Liu, Y., & Hu, X. (2025). Forecasting O3 and NO2 concentrations with spatiotemporally continuous coverage in southeastern China using a Machine learning approach. *Environment International*, *195*. https://doi.org/10.1016/j.envint.2024.109249

Manawadu, L., Wijesekera, S., & Manawadu, L. (2009). *Understanding Air Pollution Dynamics and Exploring Reasons for Aggravation of Air Pollution in the City of Colombo using Geo-statistical Techniques*. https://www.researchgate.net/publication/272686901

Sokhi, R. S., Moussiopoulos, N., Baklanov, A., Bartzis, J., Coll, I., Finardi, S., Friedrich, R., Geels, C., Grönholm, T., Halenka, T., Ketzel, M., Maragkidou, A., Matthias, V., Moldanova, J., Ntziachristos, L., Schäfer, K., Suppan, P., Tsegas, G., Carmichael, G., … Kukkonen, J. (2022). Advances in air quality research - current and emerging challenges. In *Atmospheric Chemistry and Physics* (Vol. 22, Issue 7, pp. 4615–4703). Copernicus GmbH. https://doi.org/10.5194/acp-22-4615-2022

Theys, N., De Smedt, I., Yu, H., Danckaert, T., van Gent, J., Hörmann, C., Wagner, T., Hedelt, P., Bauer, H., Romahn, F., Pedergnana, M., Loyola, D., & Van Roozendael, M. (2016). *Sulfur* *dioxide retrievals from TROPOMI onboard Sentinel-5 Precursor: Algorithm Theoretical Basis*. https://doi.org/10.5194/amt-2016-309

Theys, N., Hedelt, P., De Smedt, I., Lerot, C., Yu, H., Vlietinck, J., Pedergnana, M., Arellano, S., Galle, B., Fernandez, D., Carlito, C. J. M., Barrington, C., Taisne, B., Delgado-Granados, H., Loyola, D., & Van Roozendael, M. (2019). Global monitoring of volcanic SO 2 degassing with unprecedented resolution from TROPOMI onboard Sentinel-5 Precursor. *Scientific Reports*, *9*(1). https://doi.org/10.1038/s41598-019-39279-y

Van Geffen, J., Eskes, H., Compernolle, S., Pinardi, G., Verhoelst, T., Lambert, J. C., Sneep, M., Linden, M. Ter, Ludewig, A., Folkert Boersma, K., & Pepijn Veefkind, J. (2022). Sentinel-5P TROPOMI NO2retrieval: impact of version v2.2 improvements and comparisons with OMI and ground-based data. *Atmospheric Measurement Techniques*, *15*(7), 2037–2060. https://doi.org/10.5194/amt-15-2037-2022

Vîrghileanu, M., Săvulescu, I., Mihai, B. A., Nistor, C., & Dobre, R. (2020). Nitrogen dioxide (No2) pollution monitoring with sentinel-5p satellite imagery over europe during the coronavirus pandemic outbreak. *Remote Sensing*, *12*(21), 1–29. https://doi.org/10.3390/rs12213575