Spatiotemporal analysis and visualization of tropospheric NO_2 using Sentinel-5P satellite data and Google Earth Engine: A case study of Lombardy, Italy

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Abstract: *This study investigates the spatiotemporal variability of tropospheric nitrogen dioxide (NO_2) concentrations in the Lombardy region of Northern Italy using satellite observations from the Sentinel-5P mission. The analysis is based on time-series data acquired by the TROPOMI sensor onboard the Sentinel-5P satellite, which enables detailed monitoring of atmospheric pollutants at a regional scale. To facilitate data processing, visualization, and analysis of large volumes of satellite data, the Google Earth Engine (GEE) cloud-computing platform was used as a complementary analytical tool. The study focuses on identifying spatial patterns and temporal trends in NO_2 concentrations during the 2019–2025 period, with particular emphasis on changes observed during the COVID-19 pandemic period. Results revealed a pronounced seasonal pattern, with the highest NO_2 concentrations occurring during winter and the lowest during summer. The highest monthly concentration was recorded in December 2021 (10.40×10^{15} molecules/cm²), while the lowest occurred in July 2020 (1.95×10^{15} molecules/cm²). A substantial reduction in NO_2 concentrations was observed during the COVID-19 lockdown period, particularly in urbanized provinces such as Milan and Monza. Spatial analysis identified persistent pollution hotspots associated with densely populated and industrialized areas of the Po Valley. The results highlight the potential of satellite-based monitoring to assess air pollution dynamics and provide valuable insights into the spatial distribution of atmospheric pollutants, thereby supporting more effective environmental monitoring and air-quality management.*

Keywords: *nitrogen dioxide, Sentinel-5P TROPOMI, air pollution monitoring, Google Earth Engine*

Introduction

Air pollution is a major global environmental problem that continues to affect ecosystem functioning, environmental quality, and human health. Among atmospheric pollutants, nitrogen dioxide (NO_2) is of particular concern because it is primarily produced during high-temperature combustion processes associated with road transport, industrial production, residential heating, and energy generation (WHO 2024). As urban areas expand and industrial activity intensifies, NO_2 concentrations tend to increase, especially in densely populated and economically active regions. In the atmosphere, NO_2 participates in several chemical reactions, including the formation of nitric acid, which contributes to the development of acid rain and broader atmospheric transformations (Nathanson 2024). Due to its close association with human activities, NO_2 is widely used as an indicator of urban and industrial air pollution (Yammahi and Aung 2023). Exposure to elevated NO_2 levels has been associated with adverse respiratory and cardiovascular effects and contributes to a substantial burden of disease and premature mortality worldwide (Brauer et al. 2021). Moreover, increased concentrations of this pollutant may aggravate respiratory infections and inflammatory responses in the human respiratory system (Jurado et al. 2020). Due to its relatively short atmospheric lifetime, ranging

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from several hours to approximately one day depending on meteorological and photochemical conditions, NO_2 also serves as a useful indicator of recent anthropogenic emissions and local pollution sources (Engert et al. 2026). Monitoring the spatial and temporal dynamics of NO_2 is therefore essential for understanding air quality patterns, assessing environmental risks, and supporting evidence-based policy measures.

Following the rapid spread of SARS-CoV-2 in early 2020, many countries introduced strict lockdown measures that limited mobility, transport, and industrial production. In Italy, one of the countries most severely affected during the early stages of the pandemic, nationwide restrictions were implemented between March and May 2020. These measures resulted in a temporary reduction of anthropogenic emissions, and several studies reported significant decreases in atmospheric pollutants, particularly NO_2, during this period (Benchrif et al. 2021, Chen et al. 2020). The pandemic therefore provided a large-scale natural experiment that enabled researchers to investigate the relationship between human mobility, economic activity, and atmospheric pollution under unprecedented reductions in transport and industrial emissions (Bondonio et al. 2025, Athul et al. 2025, Wu et al. 2021).

Traditionally, air pollution monitoring has relied primarily on in situ measurements from ground-based monitoring stations. These systems are capable of measuring a wide range of pollutants with high accuracy and reliability (Yi et al. 2015). Although they provide detailed information at specific locations, their spatial coverage is often limited and unevenly distributed, resulting in an incomplete representation of atmospheric pollution patterns over larger areas. In recent decades, advances in Earth observation have substantially improved the capability to monitor trace gases from space, enabling continuous assessments across local, regional, and global scales. Satellite-based observations offer consistent and spatially extensive information on atmospheric composition and are particularly valuable where ground monitoring networks are sparse or absent. Earlier satellite instruments such as GOME aboard ERS-2, SCIAMACHY on Envisat, and OMI on the Aura satellite laid the foundation for global monitoring of atmospheric trace gases, including NO_2, by providing long-term observations of tropospheric column concentrations (Hahne et al. 1995, ESA 2012, NASA 2023). These missions significantly improved our understanding of large-scale air quality dynamics and enabled the development of global atmospheric composition datasets.

Among currently available systems, Sentinel-5P with the TROPOMI sensor represents a major step forward in atmospheric monitoring, providing high-temporal-resolution data on a wide range of trace gases, including NO_2. At the same time, cloud-based geospatial platforms have significantly expanded the analytical potential of satellite observations. Google Earth Engine (GEE) provides access to large archives of pre-processed Earth observation data and enables efficient analysis and visualization of long time series without the need for extensive local computing resources. The integration of Sentinel-5P data within GEE has made it possible to examine spatio-temporal changes in atmospheric pollutants using scalable and reproducible workflows. This is particularly relevant for regional studies seeking to evaluate long-term pollution trends, sudden disruptions in anthropogenic activity, or relationships between atmospheric composition and land-use characteristics.

Despite the growing number of studies on air quality using remote sensing, substantial regional differences in pollution dynamics remain insufficiently explored. Northern Italy, and particularly the Lombardy region within the Po Valley, represents one of the most industrialized and urbanized areas in Europe. High population density, intensive industrial activity, and major transport corridors, combined with meteorological conditions that often limit atmospheric dispersion, make the region particularly suitable for investigating spatio-temporal variability in atmospheric NO_2 concentrations.

This study focuses on the spatio-temporal distribution of NO_2 over Lombardy using a time series of Sentinel-5P observations for the period 2019–2025, processed in Google Earth Engine. The main objectives are: (i) to identify and analyse spatial and temporal patterns of atmospheric NO_2 concentrations in the study region during 2019–2025, with particular emphasis on interannual and seasonal variability and the COVID-19 lockdown period; (ii) to develop a GEE-based application for the visualization and monitoring of NO_2 dynamics. By combining satellite-based atmospheric observations with cloud-based analytical tools, the study aims to contribute to a more comprehensive understanding of regional air pollution dynamics and to demonstrate the value of accessible Earth observation platforms for air quality research.

Study area

Lombardy is a region located in northern Italy (latitude: 45°40′N; longitude: 9°30′E) covering an area of approximately 23,844 km² (fig. 1). The region lies between the Alpine mountain range in the north and the Po River basin in the south. It borders Switzerland to the north and the Italian regions of Piedmont to the west, Veneto and Trentino to the east, and Emilia Romagna to the south. Lombardy consists of eleven provinces and the metropolitan city of Milan, which also serves as the regional capital. With nearly 10 million inhabitants, it is the most populous region in Italy and one of the most densely populated regions in Europe (Maranzano 2022).

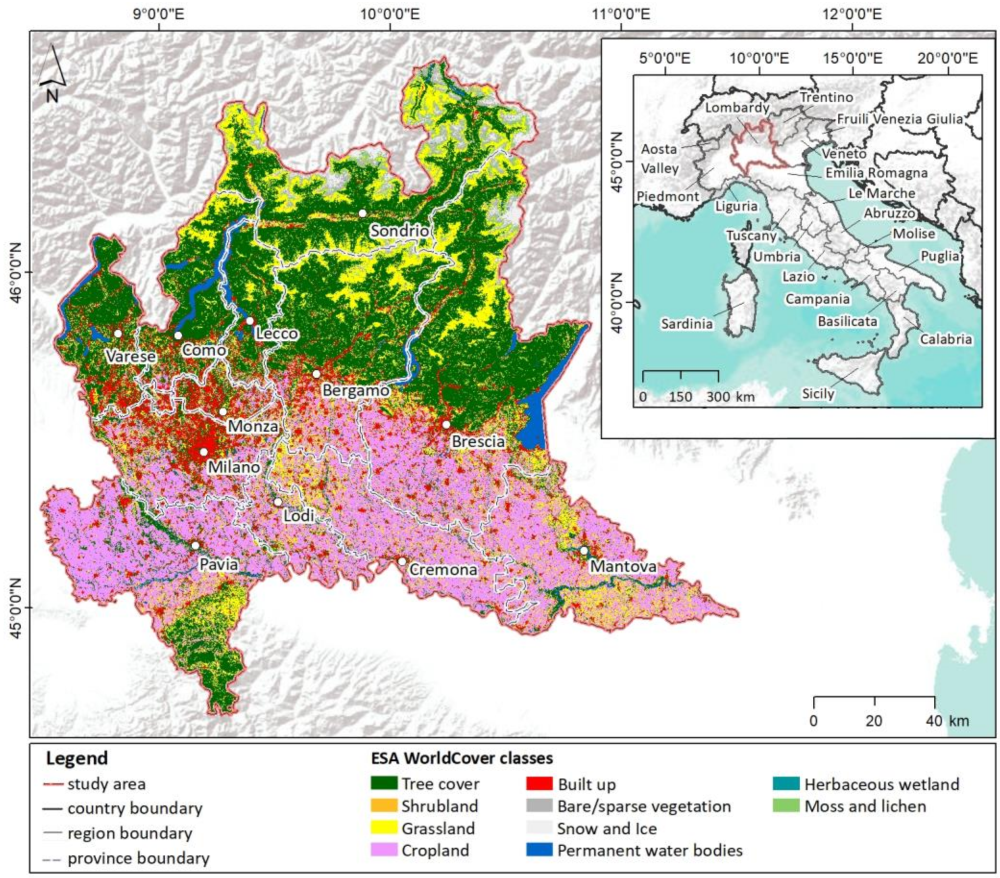

Fig. 1. *Localisation of the study area;*
Source: authors' processing based on ESA WorldCover 2021 (Zanaga et al. 2022) and FAO GAUL administrative boundaries (FAO 2015)

From a physical–geographical perspective, Lombardy can be divided into three main landscape zones: the Alpine and pre-Alpine mountainous areas in the north, the foothill zone, and the extensive lowland area of the Po Plain in the south. Mountainous terrain covers about 40% of the regional territory, while nearly half of the region consists of flat alluvial lowlands. The region includes several major river systems and pre-Alpine lakes, including Lake Como, Lake Iseo, and Lake Garda (Regione Lombardia 2020).

The region experiences a temperate climate with continental influences, characterised by hot summers and cold winters. As part of the Po Valley, one of the most polluted regions in Europe, Lombardy is frequently affected by meteorological conditions that limit atmospheric dispersion and favour pollutant accumulation. Lombardy is also one of the most economically developed and industrialised regions in Italy, with major urban centres such as Milan, Brescia, and Bergamo. Due to its high population density, intensive industrial activity, and dense transport infrastructure, the region frequently experiences elevated levels of air pollution.

Lombardy was among the European regions most severely affected during the early stages of the COVID-19 pandemic, making it a suitable case study for analysing spatio-temporal changes in atmospheric pollutants such as nitrogen dioxide (NO_2). Following the rapid spread of SARS-CoV-2 in February 2020, the region became the first major outbreak area in Europe, leading to the introduction of extensive mobility and economic restrictions (ECDC 2021). The COVID-19 pandemic was officially declared by the World Health Organization on 11 March 2020 (WHO 2020). The implementation of lockdown measures, including restrictions on mobility, transport, and industrial activities, led to a significant reduction in anthropogenic emissions. Several studies have shown that these measures contributed to a temporary improvement in air quality, particularly due to reduced traffic and industrial output (Chen et al. 2020, Benchrif et al. 2021). Therefore, Lombardy represents a valuable case study for assessing the relationship between human activity and air pollution, as well as for analysing changes in NO_2 concentrations during periods of reduced anthropogenic pressure.

Methods and data

Input data

For this study, atmospheric nitrogen dioxide (NO_2) concentrations were analysed using satellite observations from the Sentinel-5 Precursor (Sentinel-5P) mission, part of the European Earth observation programme Copernicus coordinated by the European Commission and implemented with the support of the European Space Agency (ESA). Copernicus Sentinel-5P is a near-polar sun-synchronous orbit satellite launched on 13 October 2017 as a precursor mission designed to bridge the observational gap between earlier atmospheric missions such as Envisat (SCIAMACHY) and the upcoming Sentinel-5 mission. The satellite carries the TROPOMI (Tropospheric Monitoring Instrument), a high-resolution imaging spectrometer operating in ultraviolet, visible, near-infrared, and shortwave infrared spectral ranges, enabling the detection of several atmospheric trace gases including NO_2, SO_2, ozone (O_3), carbon monoxide (CO), methane (CH_4), and formaldehyde (HCHO). Sentinel-5P provides daily global coverage with a wide swath width of approximately 2600 km, allowing consistent monitoring of atmospheric composition and air quality at regional to global scales. The TROPOMI instrument provides observations at a spatial resolution of approximately 7 × 3.5 km at nadir. Data products are available at multiple processing levels, including Level-1B radiance products and Level-2 geophysical products containing vertically integrated columns of atmospheric trace gases with additional information on cloud conditions (ESA 2021).

For this study, tropospheric NO_2 column densities were analysed using the Sentinel-5P TROPOMI OFFL Level-3 NO_2 product available in Google Earth Engine. This offline nitrogen dioxide dataset provides gridded observations of tropospheric NO_2 vertical column density derived from Sentinel-5P/TROPOMI measurements. The analysed band, tropospheric_NO2_ column_number_density, is expressed in mol/m². To improve interpretability and facilitate comparison with previous studies, the values were converted to 10^{15} molecules/cm². The OFFL product was selected because it provides more stable and consistent data than near-real-time products and is therefore more suitable for retrospective spatio-temporal analysis (Prunet et al. 2020).

Data processing

The overall workflow implemented in Google Earth Engine is summarized in fig. 2. The processing chain includes data acquisition, quality filtering, unit conversion, temporal aggregation, statistical analysis, and visualization of NO_2 dynamics. Tropospheric NO_2 column densities were converted from mol/m^2 to 10^{15} molecules/cm^2 to facilitate comparison with previous studies and commonly used atmospheric pollution metrics.

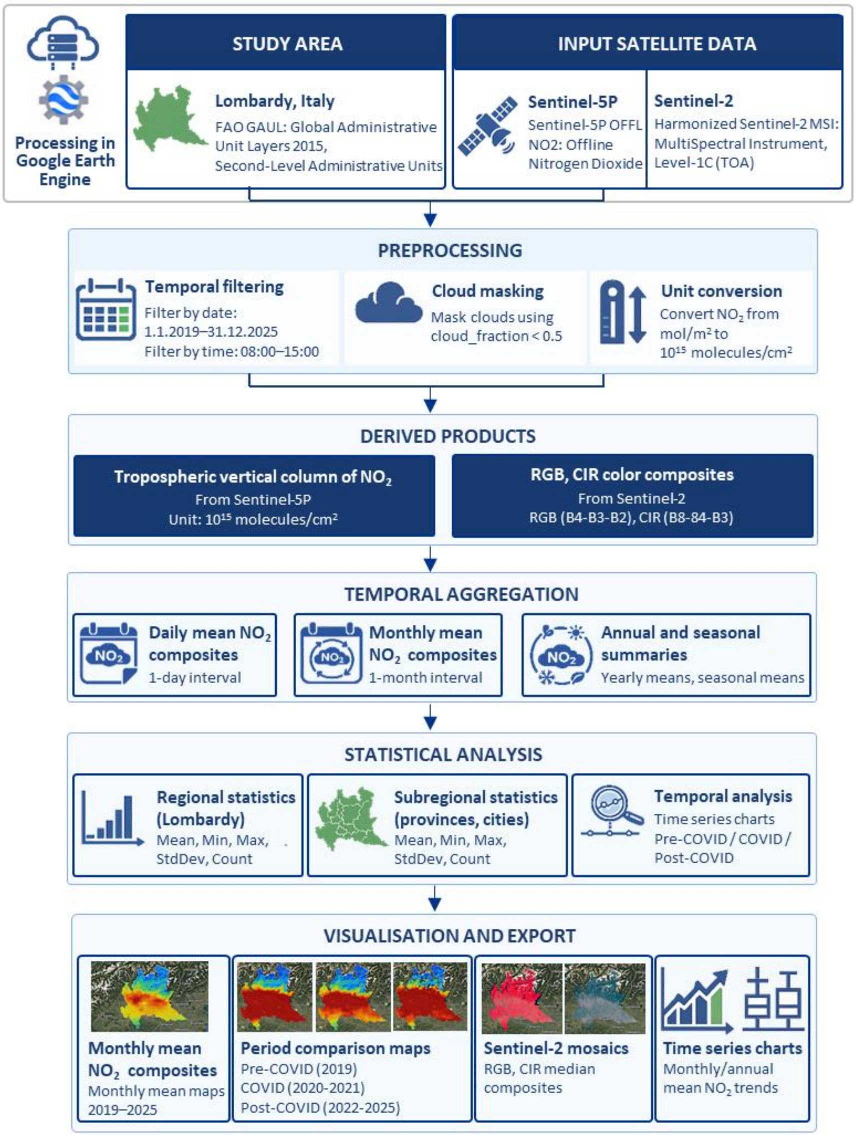

Fig. 2. *Workflow for the processing and analysis of Sentinel-5P tropospheric NO_2 data in Google Earth Engine*

The processing chain begins with the definition of the study area and visualization of its administrative boundaries. Sentinel-5P OFFL NO_2 products are subsequently filtered according to spatial extent of Lombardy, acquisition date (January 2019 – December 2025), cloud fraction, and acquisition time.

The Sentinel-5P OFFL Level-3 tropospheric NO_2 product provides tropospheric NO_2 vertical column densities in mol/m^2. To facilitate comparison with commonly used atmospheric pollution metrics and previous remote sensing studies, all values were converted to 10^{15} molecules/cm^2 using Avogadro's constant (6.022×10^{23} molecules/mol^{-1}). Individual images were clipped to the study area, and only valid observations meeting the selected quality criteria were retained for further analysis. Temporal aggregation procedures implemented within the script enable the calculation of daily mean NO_2 concentrations and the generation of monthly composite images for the 2019–2025 period. These outputs provide a continuous dataset suitable for evaluating seasonal variability and long-term changes in atmospheric pollution patterns. The application further derives descriptive statistical measures, including mean, minimum, maximum, and standard deviation values of monthly NO_2 concentrations for the analysed area.

The extracted statistics are exported as tabular outputs in CSV format for subsequent analysis outside the GEE environment. In addition, the script generates time-series charts representing monthly NO_2 dynamics for individual years and for the complete observation period. Separate line charts are also produced for individual Lombardy subregions, allowing assessment of intra-regional spatial variability in tropospheric NO_2 concentrations.

An additional component of the workflow focuses on the comparison of pre-pandemic, pandemic, and post-pandemic periods through visualization of selected monthly NO_2 concentration layers. This functionality supports the evaluation of changes in atmospheric pollution associated with COVID-19 mobility restrictions and altered anthropogenic activity. To complement the atmospheric analysis, the application also incorporates Sentinel-2 imagery for the generation of RGB and CIR composites of the study area. Median mosaics derived from cloud-filtered Sentinel-2 scenes provide supplementary spatial context for interpreting land cover characteristics and urbanized environments in relation to observed NO_2 distributions.

Satellite-based observations of atmospheric NO_2 were processed using the cloud-based geospatial analysis platform Google Earth Engine (GEE), which provides access to extensive archives of Earth observation data and scalable computational resources for large-scale spatial analyses. GEE allows efficient processing of satellite imagery and time-series datasets through JavaScript and Python APIs without the need for local data storage or high-performance computing infrastructure (Amani et al. 2020, Zhao et al. 2024).

For this study, tropospheric NO_2 column data from the Sentinel-5P TROPOMI instrument were accessed through the GEE data catalogue using the dataset Sentinel-5P OFFL NO2: Offline Nitrogen Dioxide. The analysis focused on the Lombardy region, which was extracted using administrative boundary data from the FAO Global Administrative Unit Layers (GAUL) dataset. The second administrative level (FAO/GAUL/2015/level2) was used to delineate the study area. For each valid observation, satellite scenes were clipped to the study area and relevant temporal attributes (date, year, and acquisition time) were extracted. To focus on daytime atmospheric conditions and ensure consistency between scenes, an hourly filter was applied selecting observations between 08:00 and 15:00 local time.

Daily mean NO_2 concentrations were calculated from the filtered satellite observations and subsequently aggregated into monthly averages for the entire study period. Monthly aggregation was selected to reduce short-term variability and highlight long-term trends in atmospheric NO_2 concentrations. In addition to spatial raster outputs, summary statistics including minimum, maximum, and mean monthly values were extracted and exported in tabular format for further analysis. Monthly averages were used as they provide a more comprehensive view of long-term trends in NO_2 concentrations and allow for the evaluation of whether air quality improves or deteriorates over time. This approach has been widely applied in previous studies, where monthly patterns were derived from daily observations to analyse temporal variability in air pollution (Ghasempour et al. 2021, Md. Haque et al. 2022).

To provide contextual information on land surface characteristics, additional Sentinel-2 imagery was processed in GEE. The Sentinel-2 MSI sensor provides multispectral data at spatial resolutions of 10 m, 20 m, and 60 m, depending on the spectral band. In this study, 10 m resolution bands were used. Image collections were filtered by cloud coverage (CLOUDY_PIXEL_PERCENTAGE < 2) and temporally constrained to the vegetation season between May and August 2023. Median composite images were generated to represent typical surface conditions. Two spectral visualisations were prepared: a natural colour RGB composite (bands B4–B3–B2) and a colour infrared (CIR) composite (bands B8–B4–B3). These datasets were used to visually interpret relationships between land cover types, vegetation patterns, and spatial variability of NO_2 concentrations across the study region.

To evaluate the reliability of satellite-derived NO_2 observations, monthly Sentinel-5P concentrations were compared with ground-based measurements obtained from the European Environment Agency (EEA) Air Quality e-Reporting database (EEA 2025). Five representative Lombardy cities – Milan, Bergamo, Brescia, Como and Cremona – were selected based on the availability and completeness of EEA NO_2 observations in 2025 and to represent different urban and environmental conditions within the region. For each city, hourly EEA NO_2 observations were filtered to match the Sentinel-5P daytime acquisition window and then aggregated into monthly mean concentrations. Where multiple monitoring stations were available within a city, station-level monthly means were averaged to obtain one representative city-level value. Corresponding Sentinel-5P monthly mean NO_2 values were extracted from 5 km buffers around the selected city centres. Since Sentinel-5P measures tropospheric vertical column densities (10^{15} molecules cm^2), whereas EEA stations measure near-surface concentrations ($\mu g/m^3$), the comparison focused on temporal agreement rather than direct comparison of absolute concentrations. Pearson correlation coefficients (r) and coefficients of determination (R^2) were calculated using months with valid observations in both datasets. November 2025 was excluded because no valid Sentinel-5P monthly composite was available after cloud and quality filtering.

Results

Google Earth Engine application for monitoring NO_2 concentrations using Sentinel-5P data

A cloud-based application for monitoring tropospheric NO_2 concentrations was developed in the Google Earth Engine (GEE) environment using Sentinel-5P TROPOMI observations (fig. 3). The application is implemented in JavaScript within the GEE Code Editor and enables automated processing, visualization, statistical analysis, and export of atmospheric NO_2 data for selected study areas and time periods. The developed application is publicly accessible through the GEE platform and can therefore be used or further modified for analyses in other regions and temporal periods. The source code is available via the following link:

https://code.earthengine.google.com/f05df7755a961704b573cc16bc7bf647

The open-access structure of the workflow enables reproducibility of the analysis and facilitates adaptation of the script for different atmospheric and environmental monitoring applications. The workflow was designed to provide a flexible framework for spatio-temporal analysis of air pollution. Users can modify the study area, temporal extent, visualization settings, cloud masking thresholds, and additional processing parameters according to the requirements of a specific analysis. The application allows the visualization of NO_2 concentration maps for different periods and supports comparison of individual layers through the integrated layer management interface.

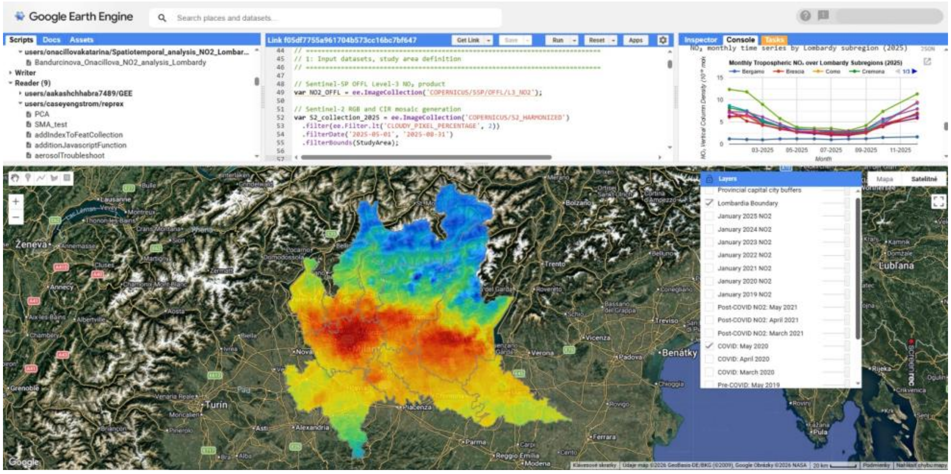

Fig. 3. *Structure of the developed Google Earth Engine application for spatiotemporal analysis of tropospheric NO_2 concentrations using Sentinel-5P satellite data over the Lombardy region, including data preprocessing, temporal aggregation, statistical analysis, visualization of NO_2 dynamics, export of outputs, and integration of Sentinel-2 imagery*

Evaluation of NO_2 concentrations in the study area

Spatio-temporal assessment of NO_2 concentrations in Lombardy during 2019–2025

The column chart comparing monthly tropospheric NO_2 concentrations over Lombardy (fig. 4) reveals a clear seasonal pattern consistent with the results observed in the line charts. The highest NO_2 concentrations occur during the winter months, while the lowest values are observed in summer. Elevated winter concentrations are primarily associated with increased residential heating, higher traffic intensity, industrial emissions, and less favourable atmospheric dispersion conditions during colder periods.

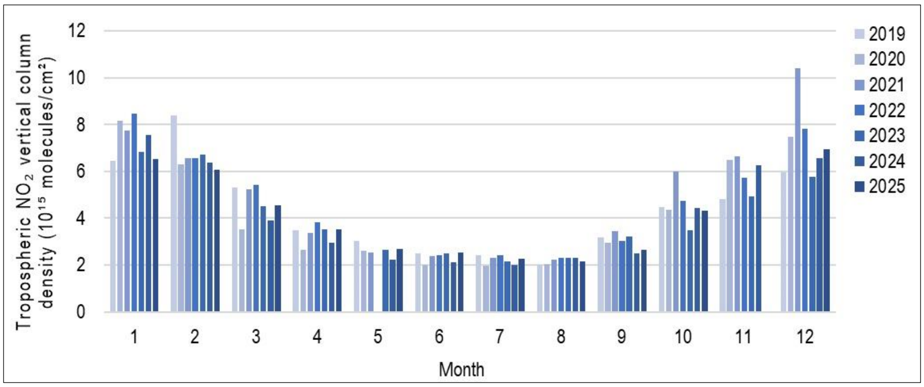

Fig. 4. *Monthly mean NO_2 concentrations in Lombardy during 2019-2025*

This seasonal behaviour is consistent across all analysed years, although some interannual variability is present. Elevated winter concentrations are further influenced by regional meteorological and geographical conditions. As noted by Maranzano (2022), Lombardy is characterised by relatively low precipitation and weak wind conditions, particularly during winter, when wind speeds rarely exceed 7 m/s. Additionally, the region's location within the Po Valley, bounded by the Alps to the north and the Apennines to the south, limits air circulation and promotes the accumulation and stagnation of atmospheric pollutants.

A pronounced reduction in NO_2 concentrations occurred during spring 2020, corresponding to the COVID-19 lockdown period in Italy. Compared with March 2019, concentrations in March 2020 decreased by approximately 2.18×10^{15} molecules/cm², while lower concentrations persisted during April-July 2020. Missing values in May 2022 are attributed to data gaps caused by cloud contamination, similarly reflected in spatial datasets. Over the entire study period, the highest NO_2 concentrations were recorded in December 2021 (10.40×10^{15} molecules/cm^2), while the lowest value occurred in July 2020 (1.95×10^{15} molecules/cm^2). Elevated values were also detected in January 2022 (8.46×10^{15} molecules/cm^2) and January 2020 (8.17×10^{15} molecules/cm^2). In contrast, the decreased concentrations were identified also in August 2019, when the concentration decreased to approximately 2.00×10^{15} molecules/cm^2. Similarly, low values were recorded in June-August 2020, ranging between approximately 1.97 and 2.32×10^{15} molecules/cm^2.

Spatial variability of monthly NO_2 concentrations, expressed as the standard deviation of monthly pixel values within Lombardy, exhibited a clear seasonal pattern – it was highest during winter months and lowest during summer. The highest spatial variability was observed in December 2021 (SD = 6.22×10^{15} molecules/cm^2), reflecting strong concentration gradients between urban-industrial areas and the mountainous northern part of the region. Conversely, the lowest variability occurred in August 2025 (SD = 0.67×10^{15} molecules/cm^2), indicating a relatively homogeneous spatial distribution of NO_2 concentrations across the region.

The decline observed during spring 2020 is clearly reflected in the monthly statistics, corresponding to the COVID-19 lockdown period in Italy. For example, concentrations in March 2020 decreased to approximately 3.51×10^{15} molecules/cm^2 compared with 5.29×10^{15} molecules/cm^2 in March 2019. Similarly, April 2020 recorded concentrations of approximately 2.64×10^{15} molecules/cm^2, which was notably lower than the 3.49×10^{15} molecules/cm^2 observed in April 2019. These decreases provide indirect evidence of the dominant contribution of transport-related emissions to regional air pollution. The strongest reductions occurred in highly urbanised provinces, suggesting that mobility restrictions had a larger influence on observed concentrations than changes in industrial activity alone. However, part of the observed reduction may also reflect interannual differences in meteorological conditions, highlighting the need for meteorological normalisation in future studies.

Following the lockdown period, NO_2 concentrations gradually increased again, particularly during autumn and winter seasons. Between 2022 and 2025, several months reached or exceeded pre-pandemic levels, indicating a recovery of economic and transportation activities. Nevertheless, the data demonstrate persistent year-to-year variability, suggesting that meteorological conditions and atmospheric circulation patterns also played an important role in shaping the spatial and temporal distribution of tropospheric NO_2 over Lombardy.

Fig. 5 illustrates the temporal variability of monthly mean tropospheric NO_2 concentrations across individual provinces of Lombardy during 2019-2025. Considerable spatial differences can be observed among the provinces. The highest NO_2 concentrations were consistently recorded in the provinces of Milan (MI), Monza and Brianza (MB), and Bergamo (BG), reflecting their high population density, intensive transport activity, and industrial development. In contrast, the lowest concentrations occurred in the mountainous province of Sondrio (SO), where anthropogenic pressures are substantially lower. The persistent contrast between Milan and Sondrio reflects fundamental differences in emission intensity and atmospheric dispersion conditions. Milan represents one of the largest urban and transportation hubs in northern Italy, whereas Sondrio is characterised by lower population density, limited industrial activity, and stronger influence of mountain ventilation processes. The observed concentration gradient therefore reflects both anthropogenic emission intensity and topographic controls on pollutant accumulation. Despite these spatial differences, all provinces exhibited a similar seasonal pattern characterised by elevated concentrations during winter months and lower values during summer. A noticeable decline in NO_2 concentrations was observed during spring 2020 across most provinces, corresponding to the COVID-19 lockdown period and associated reductions in anthropogenic activity.

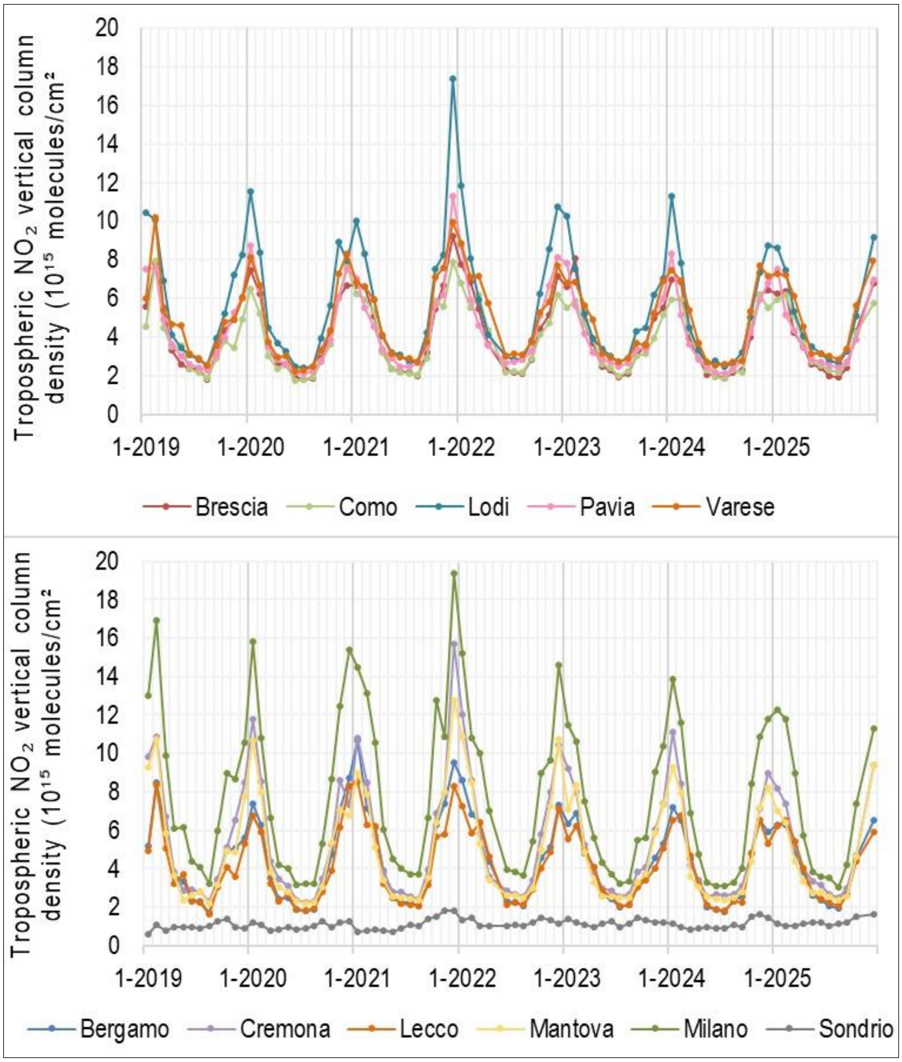

Fig. 5. *Temporal variability of monthly mean NO_2 concentrations in individual provinces of Lombardy during 2019-2025*

The spatial distribution of NO_2 concentrations in Lombardy during 2025 (fig. 6) further confirms the strong seasonal variability observed in the temporal analysis. The monthly maps indicate that the highest concentrations occurred during winter months, especially in January, February, November, and December. During these periods, elevated NO_2 values were concentrated mainly in the central and western parts of Lombardy, particularly around the metropolitan and industrialised areas of Milan, Monza-Brianza, Bergamo, and Brescia.

These regions are characterised by dense urbanisation, intensive transport infrastructure, and substantial industrial activity, which represent major sources of nitrogen oxide emissions. In contrast, substantially lower NO_2 concentrations were observed during late spring and summer months, especially between May and August 2025. During this period, the spatial distribution became considerably more homogeneous, with most of the region exhibiting relatively low concentration levels. Improved atmospheric mixing, higher boundary layer development, stronger solar radiation, and reduced heating-related emissions during summer likely contributed to enhanced pollutant dispersion and lower atmospheric accumulation.

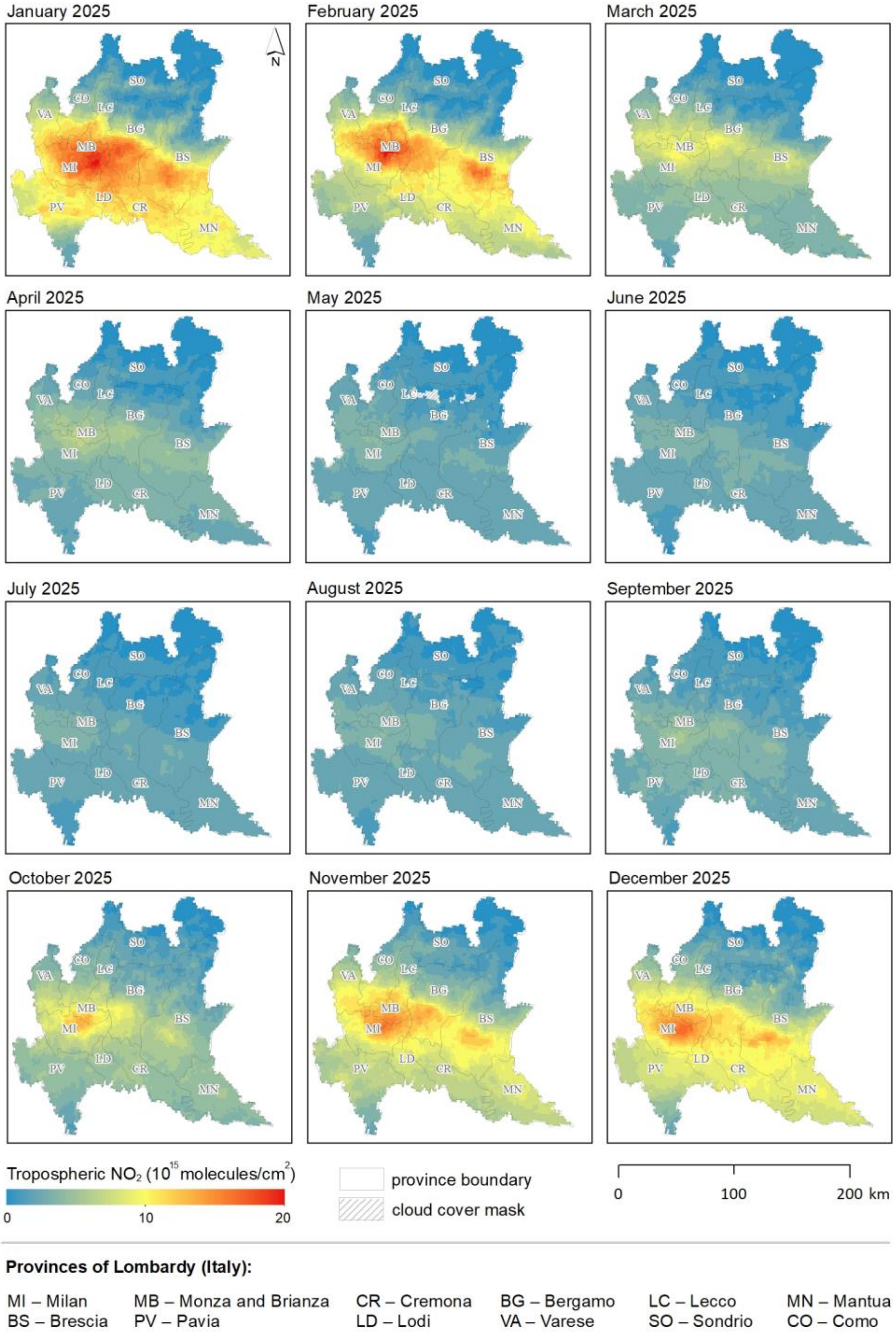

Fig. 6. *Monthly NO_2 concentrations in Lombardy during 2025*

The maps also reveal a persistent north-south gradient in NO_2 concentrations throughout the year. Lower concentrations were generally observed in the northern Alpine areas, where higher elevations, lower population density, and better ventilation conditions favour cleaner atmospheric conditions. Conversely, higher concentrations consistently occurred within the lowland Po Valley sectors, where topographic enclosure and stagnant meteorological conditions promote pollutant accumulation.

Additionally, several localised hotspots remained visible throughout colder months, indicating the influence of major urban centres and transportation corridors on regional air quality. The spatial patterns observed in 2025 therefore demonstrate the combined effects of anthropogenic emissions, seasonal meteorological variability, and the specific geographical setting of the Po Valley on the distribution of tropospheric NO_2 concentrations across Lombardy.

Assessment of the impact of COVID-19 on NO_2 concentrations

The impact of the COVID-19 pandemic on NO_2 concentrations was assessed across three distinct phases: pre-pandemic (March 2019), during the pandemic (April 2020), and post-pandemic (May 2021). The results presented in fig. 7 indicate substantial spatio-temporal variability in NO_2 concentrations associated with changes in anthropogenic activity.

During the pre-pandemic period (March 2019), NO_2 concentrations reached elevated levels across the study area, with values ranging from 0.07 to 15.25×10^{15} molecules/cm^2. A considerable portion of the region exhibited concentrations exceeding 4×10^{15} molecules/cm^2, indicating significant air pollution. The highest concentrations were detected in the metropolitan area of Milan and in the southern parts of Bergamo and Brescia, while the lowest values were observed in the mountainous region of Sondrio.

A pronounced reduction in NO_2 concentrations was observed during the pandemic period (April 2020), coinciding with the implementation of strict lockdown measures in the Lombardy region, including restrictions on transportation and human mobility. Compared to March 2019, the maximum NO_2 concentration decreased by 9.57×10^{15} molecules/cm^2. In Milan, concentrations declined from 15.25×10^{15} molecules/cm^2 to 5.68×10^{15} molecules/cm^2. The reduction was spatially widespread across the study area. An exception was identified in the Sondrio region, where a slight increase of 0.11×10^{15} molecules/cm^2 was recorded, with a minimum value of 0.18×10^{15} molecules/cm^2. This localized increase should be interpreted with caution, as it may reflect local meteorological variability, retrieval uncertainty, or other factors that were not explicitly examined in the present study. Comparable reductions in NO_2 and particulate matter concentrations during COVID-19 restrictions have been documented in previous studies (e.g., Cameletti 2020, Collivignarelli et al. 2020, Sicard et al. 2020).

In the post-pandemic phase (May 2021), NO_2 concentrations remained relatively stable compared to the lockdown period, although notable spatial differences persisted. Lower concentrations were maintained in several areas, including Mantua, Cremona, and Lodi, suggesting a partial persistence of altered mobility patterns. A decrease was also observed in the southern part of the Brescia region. The Sondrio area exhibited further reductions, with minimum values reaching -0.36×10^{15} molecules/cm^2, representing the lowest values across all analysed periods. In contrast, increased concentrations were recorded in the central part of the study area, particularly in Milan, Varese, Como, Lecco, and central parts of Bergamo, Brescia, and Pavia. In Milan, the maximum NO_2 concentration increased by 1.15×10^{15} molecules/cm^2 compared to 2020, reaching 6.83×10^{15} molecules/cm^2.

The spatial patterns identified in fig. 7 are further supported by the provincial average NO_2 concentrations presented in table 1 that summarizes the average tropospheric NO_2 concentrations for individual provinces of Lombardy during the pre-COVID (2019), COVID (2020), and post-COVID (2021) periods. In all three years, the highest concentrations were consistently observed in the highly urbanized provinces of Monza, Milan, Bergamo, and Brescia, reflecting the strong influence of road traffic, industrial activities, and population density. During the COVID-19 period, a substantial decrease in NO_2 concentrations was recorded across all provinces. For example, average concentrations in Milan decreased from 7.02×10^{15} molecules/cm^2 in April 2019 to 5.04×10^{15} molecules/cm^2 in April 2020, corresponding to a reduction of approximately 28%. Similar reductions were observed in Bergamo (−50%), Brescia (−33%), and Monza (−31%). The mountainous province of Sondrio consistently exhibited the lowest NO_2 concentrations throughout the study period, with values ranging between 0.98 and 2.11×10^{15} molecules/cm^2.

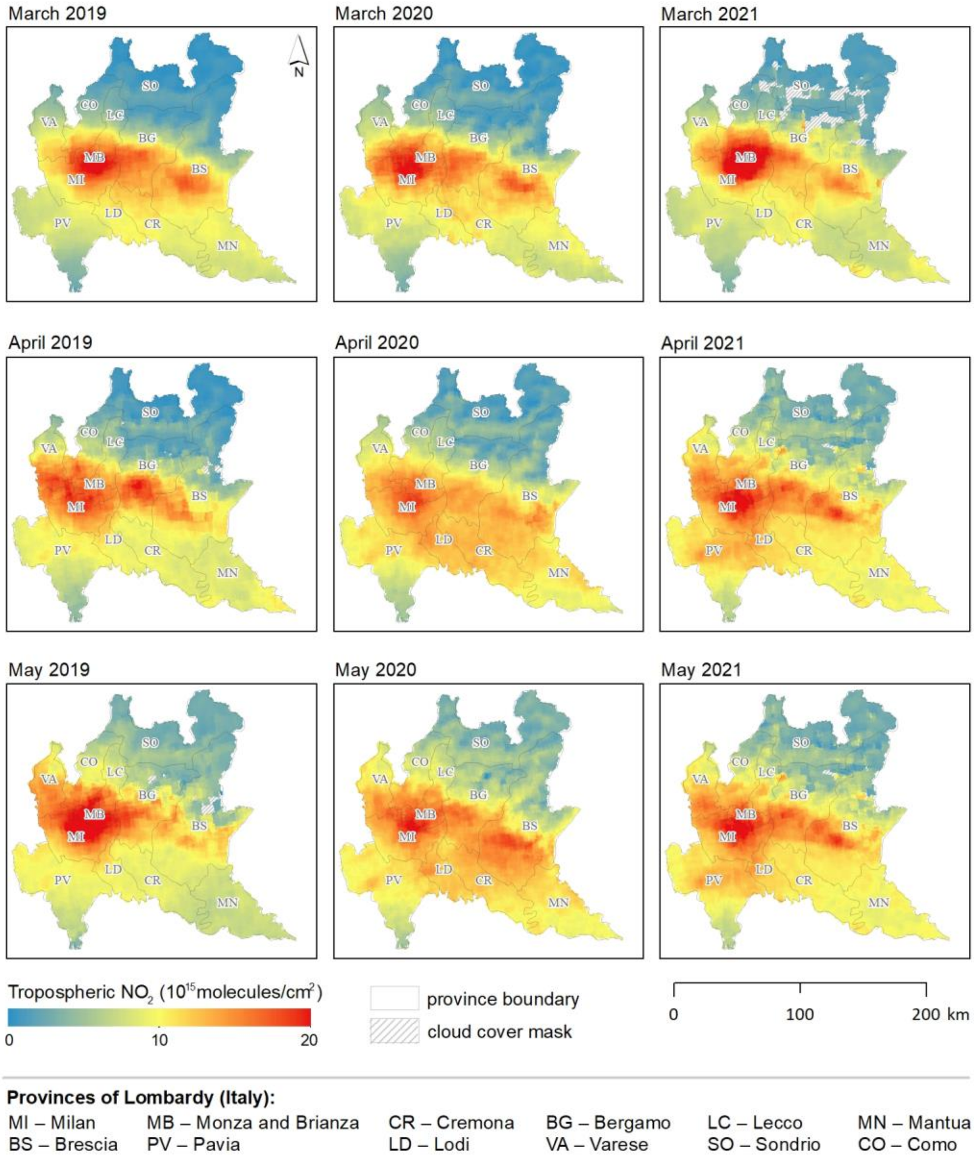

Fig. 7. *Spatial distribution of tropospheric NO_2 concentrations in Lombardy, Italy, during March-May of the pre-COVID (2019), COVID (2020), and post-COVID (2021) periods derived from Sentinel-5P/TROPOMI observations*

Following the relaxation of restrictions, NO_2 concentrations increased in several provinces during 2021, particularly in March, when Monza (17.30 × 10^{15} molecules/cm^2), Milan (12.00 × 10^{15} molecules/cm^2), Bergamo (10.08 × 10^{15} molecules/cm^2), and Brescia (10.04 × 10^{15} molecules/cm^2) reached values exceeding those observed during the pandemic year. Nevertheless, concentrations in April and May 2021 generally remained below the corresponding pre-pandemic levels, suggesting that air quality had not fully returned to conditions observed before the COVID-19 outbreak. These findings confirm the significant influence of mobility restrictions and economic slowdown on regional NO_2 emissions and highlight the dominant role of urbanized areas as persistent pollution hotspots.

Tab. 1. *Average tropospheric NO_2 concentrations (10^{15} molecules/cm^2) in Lombardy provinces during the pre-COVID (2019), COVID (2020), and post-COVID (2021) periods for March, April, and May*

City	Pre-COVID			COVID			Post-COVID		
	March	April	May	March	April	May	March	April	May
Bergamo	10,89	7,49	5,68	6,22	3,74	4,10	10,08	6,30	4,37
Brescia	11,33	5,91	4,47	7,13	3,98	4,62	10,04	5,81	4,72
Como	6,73	5,20	4,82	4,24	3,14	3,32	7,96	4,71	3,43
Cremona	6,35	3,97	3,12	4,26	3,57	3,09	5,53	3,97	2,82
Lecco	5,93	3,47	3,98	3,81	2,50	3,04	7,50	3,64	3,24
Lodi	7,35	4,18	3,65	4,67	3,80	3,42	6,25	4,21	3,36
Mantova	6,09	3,64	2,45	4,25	3,26	3,05	5,34	3,66	2,74
Milan	10,57	7,02	7,44	7,49	5,04	4,68	12,00	7,40	5,48
Monza	14,48	6,98	8,05	8,03	4,84	4,99	17,30	8,08	5,42
Pavia	5,95	4,31	3,24	4,08	3,27	2,91	5,17	4,39	3,61
Sondrio	1,33	1,54	1,29	1,25	1,12	1,22	2,11	1,14	0,98
Varese	5,06	4,32	4,46	3,31	3,03	2,82	5,78	4,14	3,00

Validation of Sentinel-5P NO_2 observations using ground-based measurements

To assess the reliability of Sentinel-5P observations, monthly NO_2 concentrations derived from Sentinel-5P (S5P) were compared with ground-based measurements from the European Environment Agency (EEA) monitoring network for five representative Lombardy cities (Milan, Bergamo, Brescia, Como and Cremona) during 2025 (tab. 2). The comparison was based on monthly mean values, allowing evaluation of the seasonal variability captured by both datasets. Because Sentinel-5P measures tropospheric vertical column densities (10^{15} molecules/cm^2) while EEA stations measure near-surface concentrations (µg/m^3), validation focused on temporal consistency rather than direct comparison of absolute concentrations.

Validation against EEA ground-based monitoring stations demonstrated very strong temporal agreement between Sentinel-5P and in situ observations. Pearson correlation coefficients ranged from 0.951 in Como to 0.979 in Brescia, while coefficients of determination (R^2) ranged from 0.905 to 0.958. All correlations were statistically significant at $p < 0.001$. The highest agreement was observed in Brescia ($r = 0.974$, $R^2 = 0.949$) and Milan ($r = 0.974$, $R^2 = 0.949$). Bergamo ($r = 0.961$, $R^2 = 0.923$) and Cremona ($r = 0.963$, $R^2 = 0.928$) also exhibited strong correspondence between satellite-derived and ground-based observations. The lowest, although still very strong, agreement was observed in Como ($r = 0.951$, $R^2 = 0.905$). Both datasets consistently reproduced the seasonal cycle characterised by elevated NO_2 concentrations during winter and lower concentrations during summer. November 2025 was excluded from the analysis because no valid Sentinel-5P monthly composite was available following cloud and quality filtering.

Tab. 2. *Monthly Sentinel-5P and EEA NO_2 observations used for validation (2025)*

Month	Milan		Bergamo		Brescia		Como		Cremona	
	S5P	EEA	S5P	EEA	S5P	EEA	S5P	EEA	S5P	EEA
Jan	12.298	43.04	6.261	42.23	6.252	38.89	5.974	45	8.163	28.11
Feb	11.764	36.86	6.254	36.06	6.361	37.96	6.214	41.78	7.385	23.98
Mar	8.947	28.15	4.857	25.65	4.232	29.59	5.142	34.79	5.096	17.97
Apr	5.743	21.4	3.854	21.11	3.515	23.86	3.821	25.73	4.023	14.23
May	3.819	16.92	2.628	17.48	2.635	23.24	2.733	21.27	3.374	11.82
Jun	3.567	15.36	2.352	16.58	2.415	23.36	2.556	22.1	3.177	13.52
Jul	3.553	15.78	2.089	15.79	1.984	21.68	2.306	21.56	2.67	12.46
Aug	3.034	12.81	1.929	11.94	1.962	18.28	2.191	16.58	2.498	11.9
Sep	4.183	21.68	2.649	16.73	2.458	25.9	2.682	22.78	2.979	14.46
Oct	7.35	30.37	4.595	24.16	4.333	30.41	4.28	27.44	4.662	19.4
Dec	11.289	40.81	6.528	34.84	6.836	39.68	5.806	33.67	9.381	25.92

Discussion

The results demonstrate that Sentinel-5P TROPOMI data processed within the Google Earth Engine (GEE) platform provide an efficient framework for analysing the spatio-temporal variability of atmospheric NO_2 concentrations over Lombardy. The cloud-based processing environment enabled consistent processing of multi-year satellite observations and facilitated the generation of comparable spatial outputs and time-series statistics. Similar advantages of GEE for large-scale air-quality analyses were reported in previous studies focusing on atmospheric trace gases and urban pollution dynamics (Singh et al. 2021, Ghasempour et al. 2021, Ayek et al. 2025).

The spatial distribution of NO_2 observed in this study corresponds well with the known environmental and socio-economic characteristics of the Lombardy region. Higher concentrations were consistently detected in the central and southern parts of the region, particularly around major urban and industrial centres such as Milan, while lower values occurred in the northern mountainous areas with lower population density and reduced anthropogenic activity. This spatial pattern is consistent with earlier studies showing that NO_2 concentrations in northern Italy are strongly influenced by urbanisation, road transport, and industrial emissions, as well as by the specific meteorological conditions of the Po Valley that favour pollutant accumulation (Piccoli et al. 2020, Maranzano 2022).

Seasonal variability observed in the time series, with higher concentrations during winter months and lower levels in summer, is also consistent with the influence of residential heating and reduced atmospheric mixing during colder periods. The pronounced seasonal variability identified in this study is consistent with observations reported for other parts of northern Italy and the wider Po Valley region. Engert et al. (2026) demonstrated that NO_2 concentrations over northern Italy exhibit a strong seasonal cycle, with elevated winter concentrations resulting from increased emissions, reduced photochemical removal, and unfavourable dispersion conditions. The topographic setting of the Po Valley, enclosed by the Alps and Apennines, further contributes to pollutant accumulation during stable atmospheric conditions. Similar mechanisms likely explain the elevated winter NO_2 concentrations observed across Lombardy in the present study. Comparable seasonal patterns have also been reported using Sentinel-5P observations in other regions, where winter NO_2 maxima were associated with increased anthropogenic emissions and reduced atmospheric dispersion, while summer minima reflected enhanced photochemical activity and more effective pollutant mixing (Singh et al. 2021, Md. Haque et al. 2022).

The observed concentration gradients are also consistent with previous studies identifying the Po Valley as one of the most polluted regions in Europe due to the combined effects of intensive anthropogenic emissions and restricted atmospheric ventilation (Crippa et al. 2016, Targa et al. 2024). The consistency of these findings suggests that the seasonal cycle observed in Lombardy reflects broader atmospheric processes affecting NO_2 variability. A noticeable decline in NO_2 concentrations was detected during the COVID-19 lockdown period, particularly when comparing pre-pandemic conditions in March 2019 with April 2020. The reduction was most evident in densely urbanised areas, highlighting the strong influence of traffic and industrial activities on atmospheric NO_2 levels. Similar decreases in air pollutants during lockdown periods were documented in several studies across Europe (Collivignarelli et al. 2020, Sicard et al. 2020). The reductions observed in Lombardy are also consistent with studies that quantified the effects of mobility restrictions on anthropogenic emissions during the pandemic.

Using high-resolution satellite imagery, Wu et al. (2021) reported substantial reductions in traffic density in major cities worldwide, including Milan, highlighting the strong relationship between transport activity and atmospheric pollution levels. Likewise, Athul et al. (2025) documented significant decreases in shipping-related NO_2 pollution during the COVID-19 lockdown period, indicating that reductions in atmospheric occurred across multiple transport sectors. Together, these findings support the interpretation that the decline observed over Lombardy was primarily driven by reduced anthropogenic activity during the lockdown period. Despite these reductions, concentrations partially increased again after the relaxation of restrictions, indicating that the improvement in air quality was largely temporary.

The results further support previous evidence that long-term reductions in NO_2 concentrations can be linked to improvements in environmental quality and public health. Bondonio et al. (2025) demonstrated that decreases in urban NO_2 pollution in Italy are associated with measurable health benefits and reduced disease burden. Although the present study focused primarily on spatio-temporal variability rather than health impacts, the observed reductions during the COVID-19 period illustrate the extent to which changes in human activity can influence atmospheric pollution levels. In addition, the spatial concentration of elevated NO_2 values around major urban centres such as Milan, Bergamo, and Brescia highlights the continued importance of transport and industrial emissions as dominant contributors to regional air pollution. The persistence of elevated NO_2 concentrations in major urban centres also agrees with observations reported by Maranzano (2022), who identified transport corridors and industrial zones as key sources of atmospheric pollution within Lombardy.

The observed spatial patterns also suggest a relationship between land-use characteristics and atmospheric NO_2 concentrations. Elevated concentrations were consistently associated with densely built-up urban and industrial areas, particularly around Milan, Monza, Bergamo, and Brescia, whereas lower concentrations occurred in mountainous and vegetated regions such as Sondrio. These findings are consistent with previous studies showing that urban land cover and transport infrastructure are major drivers of NO_2 emissions, while forested and sparsely populated areas generally exhibit lower pollution levels.

Although Sentinel-5P observations represent tropospheric column densities rather than near-surface concentrations measured by monitoring stations, the observed correlations indicate that the satellite product reliably captures temporal variability of NO_2 over Lombardy. Validation against EEA ground-based monitoring stations demonstrated very strong agreement between satellite-derived and in situ observations, with Pearson correlation coefficients ranging from 0.951 in Como to 0.979 in Brescia and coefficients of determination (R^2) ranging from 0.905 to 0.958. Despite differences in measurement principles, both datasets consistently reproduced the seasonal cycle characterised by elevated winter concentrations and reduced summer concentrations.

Previous validation studies have likewise demonstrated good agreement between TROPOMI NO_2 observations and ground-based measurements, although the reported strength of agreement varies depending on location, measurement type, spatial representativeness, and temporal aggregation (Griffin et al. 2019, Ialongo et al. 2020, Verhoelst et al. 2021). The comparatively stronger correlations observed in the present study are likely related to the use of monthly averaged observations, which reduce short-term meteorological variability and measurement noise. These findings support the suitability of Sentinel-5P observations for regional-scale monitoring of NO_2 dynamics and long-term air-quality assessment.

Some limitations should be considered when interpreting the results. Sentinel-5P observations represent tropospheric column densities rather than direct surface concentrations, and data availability can be affected by cloud cover and quality filtering. Furthermore, although Sentinel-5P provides unprecedented spatial coverage for atmospheric monitoring, its spatial resolution (approximately 7×3.5 km at nadir) remains relatively coarse compared with local-scale emission sources and ground monitoring stations. Consequently, small-scale urban gradients and local emission hotspots may not be fully resolved. Although validation against EEA monitoring stations demonstrated strong temporal agreement between satellite-derived and ground-based observations, the validation was limited to five representative Lombardy cities and the year 2025, which was selected because it provided the most complete and spatially consistent set of EEA observations. In addition, meteorological variables such as wind speed, temperature, and atmospheric stability, which strongly influence pollutant dispersion, were not explicitly incorporated in this analysis.

Consequently, part of the observed variability, including changes during the COVID-19 period, may reflect differences in meteorological conditions rather than changes in emissions alone. The analysis also focused primarily on descriptive assessment of temporal variability and did not include formal statistical testing of long-term trends or differences between periods. Future studies could therefore integrate meteorological data, longer time series, and formal trend analyses to better separate the influence of emission sources and atmospheric conditions. Nevertheless, the results confirm that Sentinel-5P observations combined with cloud-based processing platforms provide a valuable tool for regional-scale air-quality monitoring and environmental analysis.

Conclusions

This study demonstrates the potential of combining Sentinel-5P TROPOMI satellite observations with the Google Earth Engine (GEE) platform for analysing the spatio-temporal variability of atmospheric nitrogen dioxide (NO_2) concentrations. An interactive application for visualising and monitoring NO_2 concentrations was developed within GEE and applied to the Lombardy region in northern Italy.

The results reveal clear spatial patterns of NO_2 distribution, with the highest concentrations occurring in densely urbanised and industrialised areas, particularly around Milan, while significantly lower levels were observed in the mountainous northern part of the region, such as Sondrio. Seasonal variability was also evident, with the highest NO_2 concentrations typically occurring during winter months and the lowest during summer. The analysis further showed a substantial decline in NO_2 concentrations during the COVID-19 lockdown period. In comparison with pre-pandemic conditions in March 2019, the maximum NO_2 value decreased by approximately 9.57×10^{15} molecules/cm^2 in April 2020, reflecting reduced traffic, industrial activity, and overall anthropogenic emissions. However, concentrations gradually increased again after the lifting of restrictions, indicating that the improvement in air quality was largely temporary.

Overall, the study provides insight into the spatial distribution and temporal dynamics of NO_2 in one of the most polluted regions in Europe. The developed GEE workflow offers a flexible tool that can be easily adapted for other regions, time periods, or atmospheric pollutants. Future research should incorporate additional factors influencing air pollution, particularly meteorological variables such as wind speed, wind direction, and temperature, in order to better understand the mechanisms controlling pollutant dispersion and accumulation.

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