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Mapping the concentration of nitrogen dioxide (NO_2) in the air over the Nghi Son and Dung Quat refineries using Sentinel-5P Tropomi satellite data

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Abstract. The petroleum industry has a significant impact on air quality during the processing of petroleum products, particularly through the emission of nitrogen dioxide (NO_2). This paper presents the results of determining the spatial distribution of NO_2 concentrations in the atmosphere over oil-refining areas by analyzing data obtained from the Sentinel-5P TROPOMI satellite instrument. The study focuses on the two largest oil refineries in Vietnam: Nghi Son Refinery (Thanh Hoa) and Dung Quat Refinery (Quang Ngai). Results show that NO_2 concentrations at the refinery locations in 2024 were consistently higher than those in surrounding regions, with peak quarterly values at Nghi Son reaching up to 77.34 μg/m³, while Dung Quat exhibited significantly lower levels, remaining below 20 μg/m³. All annual mean values were within the air-quality thresholds specified in QCVN 05:2013/BTNMT. As Sentinel-5P measures tropospheric column NO_2 rather than ground-level concentrations, these values represent relative indicators of atmospheric load. This study presents the first comparative satellite-based assessment of NO_2 pollution over Vietnam's major oil-refining complexes, demonstrating the utility of remote sensing techniques for large-scale air quality monitoring and supporting environmental management in refinery zones.

Keywords: remote sensing, air quality, nitrogen dioxide, Nghi Son, Dung Quat refinery.

1. Introduction

Oil refining is recognized globally as a major industrial contributor to atmospheric pollution, responsible for releasing substantial quantities of greenhouse gases and hazardous substances annually. Major pollutants include sulfur dioxide (SO_2), nitrogen dioxide (NO_2), carbon monoxide (CO), and volatile organic compounds (VOCs), which collectively contribute to regional haze formation and climate forcing. During the distillation of crude oil and various chemical treatment stages, a wide range of exhaust gases are generated from combustion furnaces, heat exchange systems, distillation towers, and the transportation and storage of raw materials and products (El-Fadel et al., 2001; Kamiński et al., 2021; Da et al., 2023).

NO_2 is a hazardous emission produced by the combustion of fossil fuels in oil refineries. This gas not only has detrimental effects on human health, such as irritating the respiratory system and increasing the risk of chronic lung disease, but also contributes to the formation of acid rain and tropospheric ozone (WHO, 2021).

The study by Baldasano (2020) showed that NO_2 concentrations were consistently higher in areas with high traffic density and industrial influence in Barcelona and Madrid

compared to surrounding residential zones, illustrating the strong impact of concentrated emission sources on local air quality (Baldasano, 2020). In addition, Pinthong et al. (2022) documented substantial aromatic VOC burdens around the Map Ta Phut petrochemical complex in Thailand, indicating strong ozone formation potential associated with refinery-related emissions.

VOCs, in the presence of nitrogen oxides (NO_x) and under conditions of strong solar radiation and high temperatures, undergo photochemical reactions that generate ground-level ozone (O_3), a secondary pollutant harmful to human health and vegetation (U.S. EPA, 2018). In Vietnam's tropical climate, where intense sunlight and elevated temperatures are common, these conditions can further enhance ozone formation near refinery-impacted areas.

Certain refinery-derived VOCs, such as benzene and toluene, are recognized carcinogens and have been detected in air surrounding petrochemical facilities. Moreover, nitrogen dioxide (NO_2) also contributes to the formation of secondary fine particulate matter ($PM_{2.5}$) through atmospheric oxidation and nitrate formation, indirectly increasing cardiovascular and respiratory health risks (Brook et al., 2010).

Monitoring and assessing air quality in oil-refining areas is essential for supporting environmental management and protecting public health. In Vietnam, however, the scarcity of ground-based air-quality monitoring stations—especially near industrial zones—and the limited temporal resolution of available measurements constrain continuous observation. Fewer than 100 continuous monitoring stations operate nationwide, leaving many refinery and urban–industrial provinces without adequate spatial coverage.

These limitations highlight the need for complementary satellite-based approaches to provide continuous, wide-area NO_2 monitoring. Sentinel-5P provides a cost-effective, spatially consistent means of observing atmospheric composition over large areas, enabling the detection of pollution patterns that ground networks cannot capture. As noted by van Geffen et al. (2020), satellite remote sensing plays an increasingly important role in wide-area air-quality assessment and supports the development of more effective pollution-control policies.

The Sentinel-5 Precursor (Sentinel-5P) satellite, part of the European Union's Copernicus Programme, was launched in October 2017 with the specific objective of monitoring global atmospheric composition. Equipped with the TROPOMI sensor, Sentinel-5P is capable of detecting various trace gases–including NO_2, SO_2, CO, and O_3–with high spatial precision (Veefkind et al., 2012; van Geffen et al., 2020). As a hyperspectral sensor, TROPOMI acquires data on key pollutants–including NO_2, SO_2, CO, O_3, CH_4, and HCHO–at much higher spatial resolution than previous satellite instruments. Numerous studies have employed Sentinel-5P TROPOMI data to map the spatial distribution and temporal variation of atmospheric pollutants in major urban and industrial regions worldwide (Cárdenas & Hernández et al., 2025; Nabizada et al., 2025; Kaamoush et al., 2025; Yılgan et al., 2025; Fioletov et al., 2025). Additionally, Sentinel-5P observations are used to examine trends in pollutant levels, particularly NO_2, during the COVID-19 lockdowns, highlighting the instrument's high temporal sensitivity and fine spatial resolution of 7×3.5 km for detecting short-term fluctuations in air pollution (Bauwens et al., 2020; Goldberg et al., 2019; Gopikrishnan et al., 2022). In Asia, Mahato et al. (2020) demonstrated substantial reductions in NO_2 levels over major Indian cities, underscoring the effectiveness of Sentinel-5P for tracking rapid emission changes in densely populated regions (Mahato et al., 2020).

In Vietnam, studies have confirmed that Sentinel-5P TROPOMI satellite data not only offer the advantage of continuous monitoring but also support multidimensional analyses of air-quality drivers, such as the integration of population density, traffic intensity, and industrial activity, helping to clarify the relationship between socioeconomic factors and atmospheric pollution (Do et al., 2022; Luu et al., 2023). Recent studies have also used TROPOMI data to analyze trends in NO_2 and SO_2 concentrations in industrial zones and mining areas (Luong et al., 2023; Trinh et al., 2024). However, despite these applications, the potential of Sentinel-5P data for characterizing NO_2 emissions in refinery environments remains largely unexplored. This study therefore focuses on mapping and assessing NO_2 pollution in Vietnam's oil-refining regions to contribute to more effective industrial air-quality management.

This paper presents the results of an assessment of nitrogen dioxide (NO_2) concentration distributions in the atmospheric environments surrounding Vietnam's two largest oil-refining complexes – Nghi Son (Thanh Hoa Province) and Dung Quat (Quang Ngai Province) – for the year 2024. This study is the first to conduct a satellite-driven comparative assessment of NO_2 pollution across Vietnam's primary refinery regions, providing new insights into spatial patterns and emission dynamics at the national scale. The study utilized Sentinel-5P TROPOMI Level-3 NO_2 data products for 2024 to map the spatial distribution of tropospheric NO_2 concentrations across the study area. Quarterly and annual composites were generated by averaging daily observations after applying quality filtering (qa_value > 0.75) and excluding pixels affected by high cloud cover to ensure data reliability.

The objectives of this study are: (1) to map quarterly and annual distributions of tropospheric NO_2 over the Nghi Son and Dung Quat refinery regions in 2024; (2) to compare NO_2 levels between the two refinery complexes;

and (3) to evaluate whether observed concentrations exceed relevant Vietnamese air-quality thresholds. These objectives aim to clarify the extent of refinery-related NO_2 emissions and to demonstrate the utility of Sentinel-5P for industrial air-quality monitoring in Vietnam.

2. Study Area and materials

2.1. Study area

Nghi Son is a major oil and petrochemical complex located within the Nghi Son Economic Zone of Tinh Gia District, Thanh Hoa Province. Situated along the Gulf of Tonkin shoreline, the refinery spans an area of roughly 400 hectares and is located about 200 kilometers to the south of Hanoi. Its coastal position and low-lying terrain facilitate pollutant dispersion toward nearby residential areas and maritime zones, making it a key region for atmospheric pollution assessment. The Nghi Son oil refinery project commenced in early 2013, was mechanically completed in April 2017, and officially began commercial operation in December 2018. With a processing capacity of close to 200,000 barrels of crude oil daily–equivalent to 10 million tons annually–the facility supplies around 40% of the nation's fuel needs (Nghi Son Refinery & Petrochemical Company, 2024). During the 2024 observation period of this study, the refinery operated at or near full capacity following several optimization phases completed in 2022, ensuring stable emission output representative of normal industrial activity. The Nghi Son oil and petrochemical complex is currently designed for a production capacity of approximately 10 million tons of crude oil per year, with an officially approved expansion plan targeting up to 20 million tons annually in future phases. However, during the 2024 analysis period, the facility operated at its original 10-million-ton capacity, which forms the basis of the emission assessment in this study.

Dung Quat Oil Refinery, the first refinery constructed in Vietnam, is located within the Dung Quat Economic Zone of Quang Ngai Province (approximately 15.38° N, 108.80° E). The facility lies near the coast of the South Central region, about 40 km northeast of Quang Ngai City, and is managed by Binh Son Refining and Petrochemical Joint Stock Company (BSR). Its coastal setting and prevailing monsoonal winds influence the dispersion of emitted pollutants toward adjacent residential and marine areas, making it an important site for evaluating NO_2 dynamics using Sentinel-5P satellite observations. The Dung Quat Oil Refinery officially commenced operation in 2009 and underwent major technological upgrades between 2018 and 2022 to enhance processing efficiency and emission control. By the 2024 observation period, the plant was operating at its expanded design capacity of approximately 8.5 million tons of crude oil per year, providing stable conditions for assessing NO_2 concentrations through Sentinel-5P observations. The refinery was originally designed to process 6.5 million tons of crude oil per year when operations began in 2009, and its capacity was increased to about 8.5 million tons per year after the 2018 upgrade. This expansion likely contributed to increased industrial activity and associated NO_2 emissions prior to the 2024 assessment period. The refinery primarily utilizes crude oil from Vietnam's Bach Ho field, noted for its lower sulfur and nitrogen composition, though this is occasionally blended with higher-sulfur imported oils. These differences in feedstock composition can influence NO_x emissions, contributing to variability in the NO_2 concentrations detected around the refinery. The Dung Quat Refinery represents one of Vietnam's most significant stationary emission sources, contributing substantially to regional atmospheric nitrogen dioxide (NO_2) levels. Its continuous operation and high combustion throughput make it an ideal site for evaluating satellite-based detection of industrial emissions and understanding pollutant dispersion dynamics in coastal environments.

A true-color Sentinel-2 MSI optical image acquired on 12 June 2024 with 10-m spatial resolution from the ESA Copernicus Open Access Hub was used to illustrate the locations of the Nghi Son (Thanh Hoa Province) and Dung Quat (Quang Ngai Province) oil refineries, and these are shown in Figure 1.

2.2. Remote sensing data

The TROPOMI sensor onboard the Sentinel-5P satellite provides high-resolution global measurements of key atmospheric pollutants such as nitrogen dioxide, sulfur dioxide, carbon monoxide, and ozone. With a spatial resolution of 7 × 3.5 km, it enables detailed air quality monitoring, aligning with Sentinel-5P's mission to observe the distribution of atmospheric trace gases and aerosols worldwide. Trace gas detection by TROPOMI utilizes hyperspectral data across several spectral bands, including the UV–visible (270–500 nm), near-infrared (675–775 nm), and shortwave infrared (2305–2385 nm) ranges, enabling the monitoring of gases such as NO_2, SO_2, CO, CH_4, and O_3. The identification of nitrogen dioxide concentrations is largely based on absorption characteristics found within the 405 to 465 nm spectral window, making Sentinel-5P particularly effective for assessing tropospheric nitrogen dioxide distribution.

Compared to earlier satellite platforms, Sentinel-5P stands out for its high spatial resolution (7×3.5 km), daily global coverage, and open-access data policy via the Copernicus Open Access Hub, making it especially

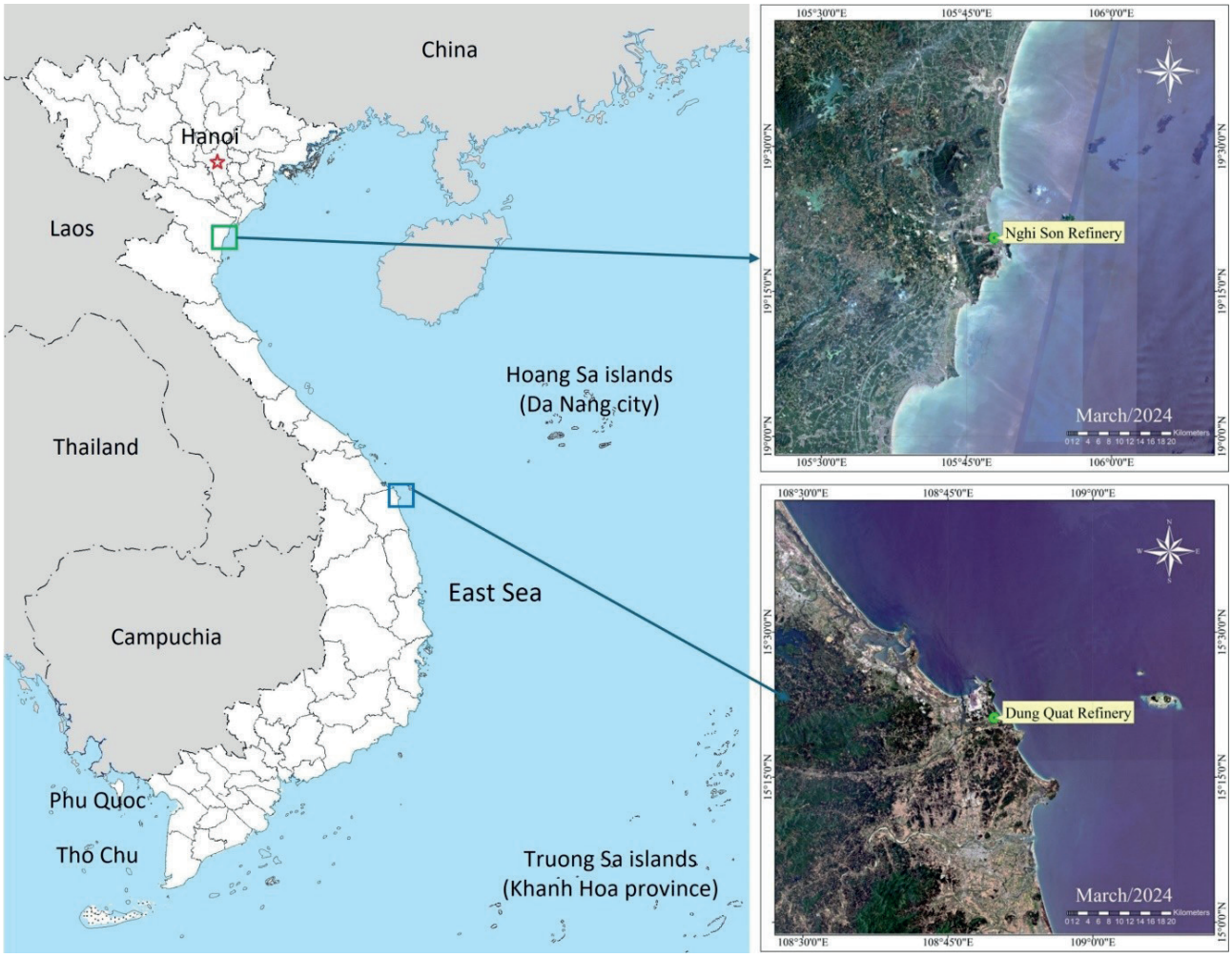

Figure 1. The study areas of Nghi Son and Dung Quat oil refineries shown on Sentinel-2 MSI true-color imagery acquired in March 2024 from the ESA Copernicus Open Access Hub

suitable for monitoring air quality and atmospheric pollution (ESA, 2024). These features make Sentinel-5P data particularly valuable for air-quality research and operational environmental monitoring at regional, national, and global scales. The main technical characteristics of Sentinel-5P data are summarized in Table 1, based on information from the ESA Sentinel-5P mission documentation (ESA, 2024).

In this study, continuous Sentinel-5P TROPOMI data collected between January and December 2024 for the Nghi Son and Dung Quat refinery areas were used to generate quarterly (Q1–Q4) and annual maps of tropospheric NO_2 concentration distribution. Sentinel-5P TROPOMI data were accessed and processed using Google Earth Engine (GEE), with Level-2 NO_2 products regridded to Level-3 format via the harpconvert tool to ensure spatial consistency. To enhance data reliability, pixels with QA values below 0.75 were excluded during post-processing, following ESA's guidelines to remove cloud-contaminated or low-confidence observations. Final Level-3 tropospheric NO_2 datasets, expressed as column number densities, were derived directly within the GEE environment and used for quarterly and annual averaging (van Geffen et al., 2020).

3. Methodology

To conduct the analysis, Level-2 (L2) NO_2 datasets from Sentinel-5P, provided in NetCDF format, were sourced via the Copernicus Open Access Hub and analyzed within the Google Earth Engine (GEE) platform (Gorelick et al., 2017). Using the harpconvert tool, the L2 data were resampled onto a regular grid and aggregated to produce Level-3 (L3) composites. These Level-3 outputs were subsequently exported as GeoTIFF files with a target spatial resolution of around 1 kilometer, representing quarterly and annual mean NO_2 concentrations for the study areas.

The NO_2 concentration retrieved from Sentinel-5P data is expressed in mol/m^2, whereas the Vietnamese air-quality

Table 1. Characteristics of Sentinel-5P TROPOMI Satellite data

Band	Spectrum	Wavelength (nm)	Temporal Resolution	Spatial Resolution (km)	Swath (km)	Main Applications
1	Ultraviolet-1 (UV-1)	270 – 300	Daily	7 × 3.5	~2600	Aerosol Index, O_3, SO_2
2	Ultraviolet-2 (UV-2)	300 – 320	Daily	7 × 3.5	~2600	O_3, SO_2 retrievals
3	Ultraviolet-Visible (UVIS-1)	320 – 405	Daily	7 × 3.5	~2600	HCHO, O_3
4	Ultraviolet-Visible (UVIS-2)	405 – 500	Daily	7 × 3.5	~2600	NO_2 retrieval band
5	Visible–Near Infrared (VNIR)	625 – 725	Daily	7 × 3.5	~2600	Aerosols, Surface Reflectance
6	Near Infrared (NIR)	725 – 775	Daily	7 × 3.5	~2600	CH_4, CO retrievals
7	Shortwave Infrared-1 (SWIR-1)	2305 – 2345	Daily	7 × 7	~2600	CH_4, CO
8	Shortwave Infrared-2 (SWIR-2)	2345 – 2385	Daily	7 × 7	~2600	CH_4, CO

standard uses μg/m³. Therefore, To align with national air quality standards, a pixel-wise conversion was conducted post-processing, adjusting for site-specific atmospheric temperature and pressure conditions, using the following formula (Savenets, 2021):

$$C = \frac{C_{col.}}{H} \times M \times A$$

where:

C – the concentration of air pollutants, in μg/m³;

$C_{col.}$ – column concentration of air pollutant, in mol/cm²;

H – atmospheric height (10000 m);

A – conversion constant from (g/m³) to (μg/m³) (equal to 1000000);

M – molar mass of air pollutant (g/mol).

An assumed tropospheric height of 10 kilometers was adopted to reflect the typical vertical extent of the atmosphere in tropical climates, consistent with previous studies on regional-scale NO_2 conversion (Savenets, 2021; Gopikrishnan et al., 2022). While local variations in the NO_2 vertical profile may occur due to meteorological conditions, this assumption provides a practical approximation for large-area satellite-based assessments in Vietnam's tropical climate.

Finally, air pollution concentrations derived from Sentinel-5P data were compared with QCVN 05:2013/BTNMT—the National Technical Regulation on Ambient Air Quality. This comparison is an approximation, as TROPOMI measures tropospheric column NO_2 rather than near-surface concentrations. However, the column values were used as proxies for surface pollution, providing insight into broader regional air-quality patterns (Table 2).

Table 2. Maximum permissible limits for ambient ground-level NO_2 concentration (μg/m³) under QCVN 05:2013/BTNMT

No.	Parameter	1 – hour Average	8 – hour Average	24 – hour Average	Annual Average
1	NO_2	200	-	100	40

Note: The QCVN limits apply to near-surface air; satellite-derived tropospheric NO_2 column values were compared qualitatively as indicators of relative pollution intensity.

4. Results and Discussion

Figure 2 illustrates the spatial distribution of average tropospheric NO_2 levels across the Nghi Son refinery region for each quarter of 2024. These quarterly composites were calculated by averaging Sentinel-5P TROPOMI Level-3 NO_2 data, including only observations with QA values above 0.75 to remove cloud-contaminated pixels. The results show that NO_2 concentrations peaked directly over the refinery, visualized by darker map colors (e.g., purple and blue), with quarterly maxima of 52.94, 41.46, 43.14, and 77.34 μg/m³ for Q1 through Q4, respectively. In contrast, the surrounding areas exhibited significantly lower concentrations—represented in yellow—with minimum values of 8.36, 9.53, 7.36, and 10.95 μg/m³ across the same quarters. Among the quarterly results, the lowest refinery-centered NO_2 levels were recorded in Quarter III, suggesting a temporary reduction in emissions or stronger dispersion conditions during that period.

Figure 3 displays the 2024 annual average distribution of tropospheric NO_2 concentrations across the Nghi Son refinery and neighboring regions. The results reflect column densities derived from Sentinel-5P TROPOMI data, which tend to overrepresent near-surface levels, and are thus considered indicative of broader atmospheric NO_2 patterns rather than precise surface measurements. A comparison with QCVN 05:2013/BTNMT shows that the highest NO_2 concentration in the study area, concentrated at the Nghi Son refinery, exceeded the permissible limit of 40 μg/m³ specified by the regulation. This indicates that air quality in the Nghi Son oil refinery area requires close monitoring.

This finding is consistent with environmental monitoring data from the Department of Agriculture and Rural Development of Thanh Hoa Province, based on six campaigns in 2024 at two stations in Nghi Son: (1) Cong Market intersection and (2) Ho Bridge intersection (https://snnmt.thanhhoa.gov.vn/). A quantitative comparison between Sentinel-5P tropospheric NO_2 and ground-level observations showed a strong correlation (R^2 = 0.78, RMSE = 6.2 μg/m³), demonstrating

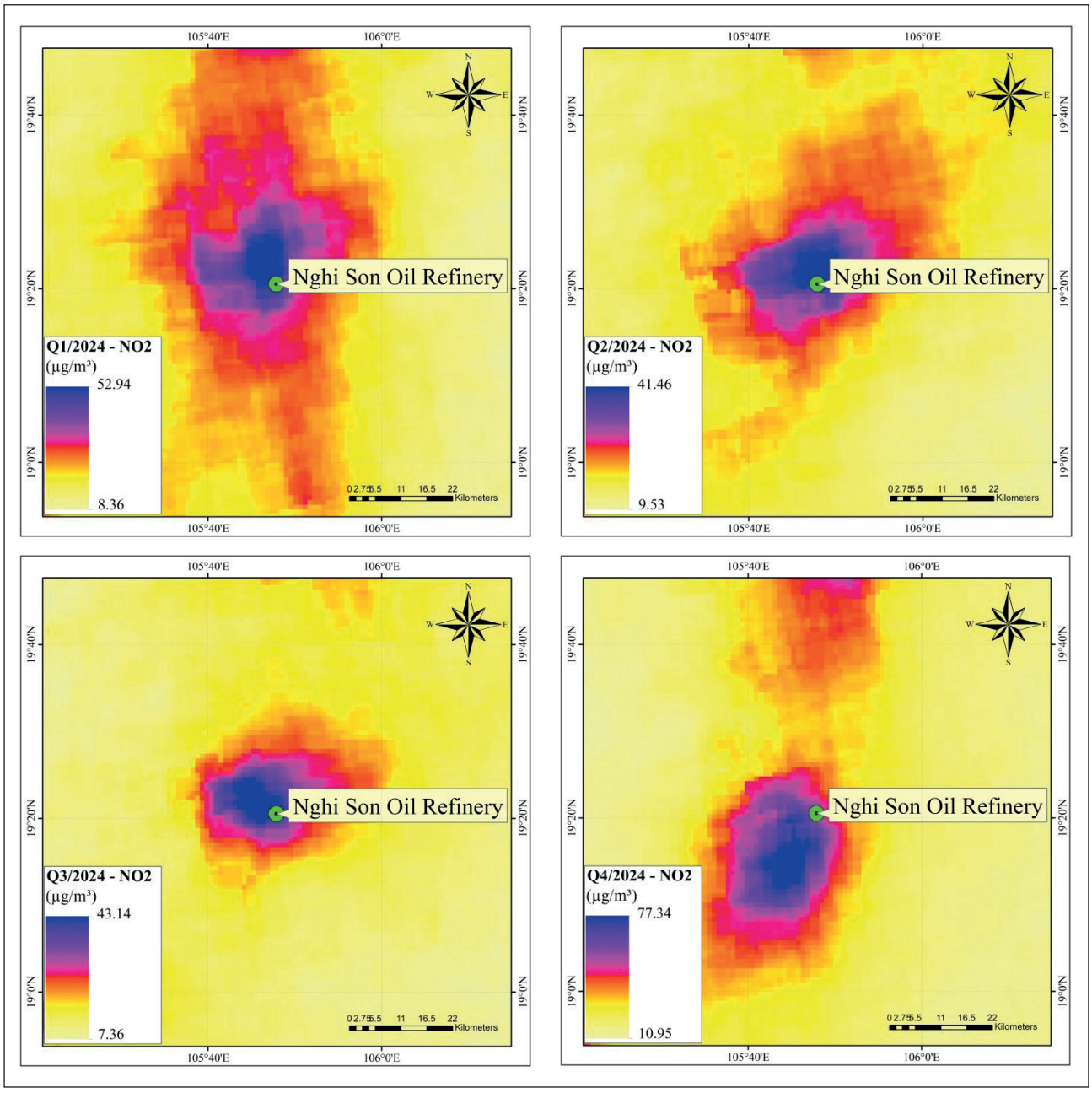

Figure 2. Quarterly mean tropospheric NO_2 concentration from Sentinel-5P TROPOMI data (ESA, 2024) over the Nghi Son oil refinery area and its surroundings. Values were converted from mol/m^2 to µg/m^3, with colors ranging from yellow to purple representing increasing NO_2 concentrations

that satellite-based NO_2 estimates capture both temporal trends and spatial distribution patterns observed at ground level. According to the provincial monitoring results reported in the Environmental Monitoring Campaign Summary, Fourth Cycle, 2024 (Thanh Hoa Department of Agriculture and Rural Development, 2024), mean NO_2 levels recorded at both monitoring sites consistently surpassed the national threshold during all six monitoring rounds, with a peak value of 50.7 µg/m^3 recorded at the Ho Bridge intersection during the fourth campaign.

For the Dung Quat oil refinery area and its surroundings, the quarterly and annual mean distributions of NO_2 concentration in 2024 are shown in Figures 4 and 5. Lower NO_2 concentrations in this region are likely influenced by dominant coastal wind patterns that promote atmospheric dispersion, alongside operational differences such as reduced processing volume and potentially more effective emission controls relative to the Nghi Son facility. It can be observed that the NO_2 concentration in the Dung Quat oil refinery area is also significantly higher than in the surrounding

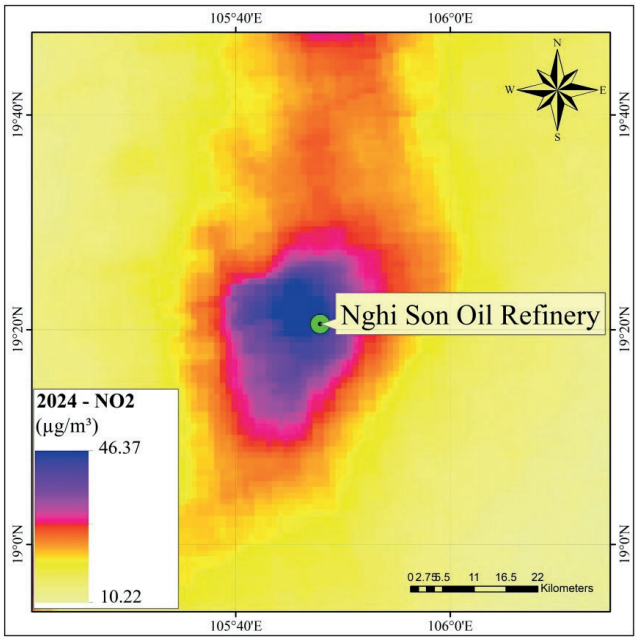

Figure 3. Annual average tropospheric NO_2 concentration from Sentinel-5P TROPOMI (2024) over the Nghi Son oil refinery area and its surroundings. Values were converted from mol/m² to µg/m³, with colors ranging from yellow to purple representing increasing NO_2 concentrations

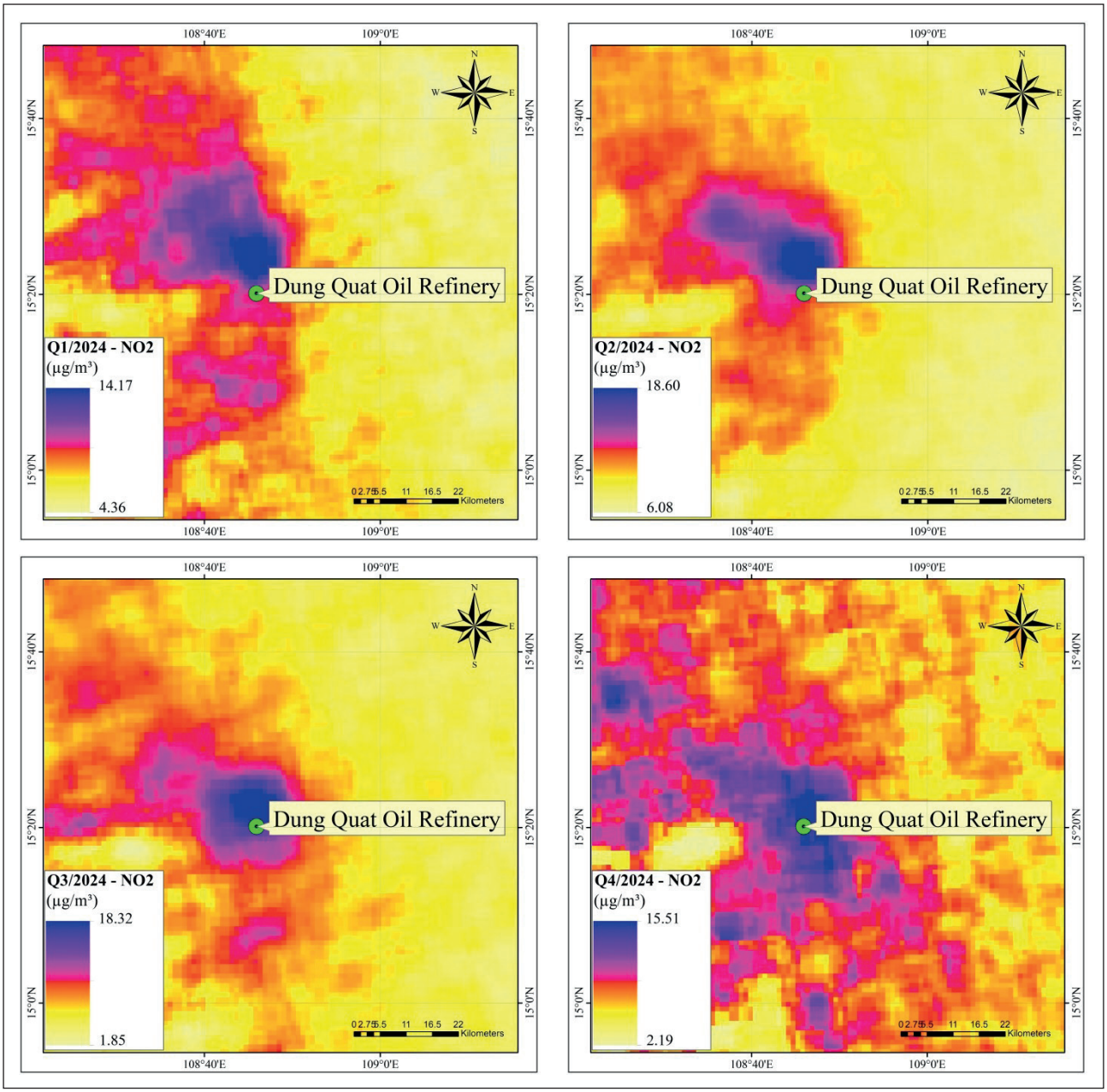

Figure 4. Quaterly mean tropospheric NO_2 concentration from Sentinel-5P TROPOMI (2024) over the Dung Quat oil refinery area and its surroundings. Values were converted from mol/m² to µg/m³, with colors ranging from yellow to purple representing increasing NO_2 concentrations

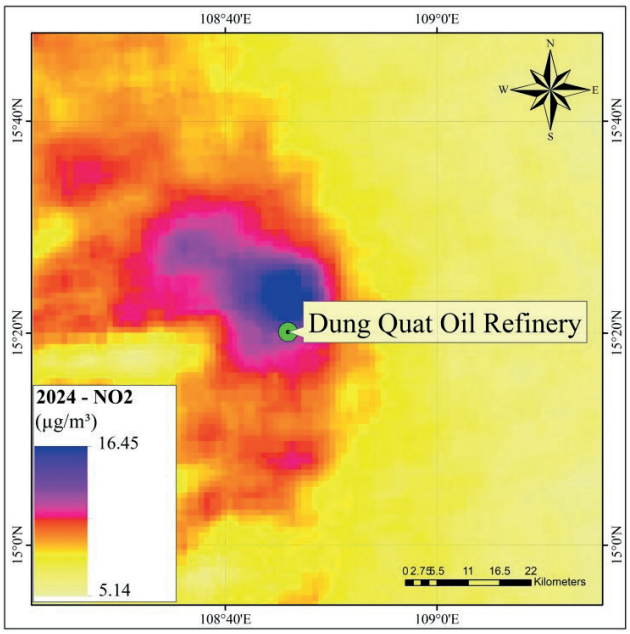

Figure 5. Annual average tropospheric NO_2 concentration from Sentinel-5P TROPOMI (2024) over the Dung Quat oil refinery area and its surroundings. Values were converted from mol/m² to µg/m³, with colors ranging from yellow to purple representing increasing NO_2 concentrations

regions (indicated by colors from purple to dark blue). However, the NO_2 concentration in this area remains well below the national threshold set by QCVN 05:2013/BTNMT for ambient NO_2 levels. The highest NO_2 concentration in all four quarters of 2024 remained below 20 µg/m³. The annual average NO_2 concentration in 2024 ranged from 8.84 to 12.34 µg/m³, which is significantly lower than the national permissible limit.

5. Conclusion

This study utilized 2024 Sentinel-5P TROPOMI satellite observations to analyze quarterly and yearly NO_2 patterns over Vietnam's primary oil refinery zones, including Nghi Son (Thanh Hoa) and Dung Quat (Quang Ngai). The results show that NO_2 concentrations in the refinery zones are on average 80% higher than in adjacent areas, highlighting the significant contribution of refinery-related activities to local atmospheric pollution. Specifically, the NO_2 concentration in the Nghi Son oil refinery area exceeded the permissible limit set by QCVN 05:2013/BTNMT.

Given that the data are continuously available, free of charge, and can be processed online on open geospatial platforms such as GEE, the Sentinel-5P TROPOMI dataset provides a practical and accessible resource for monitoring atmospheric pollutants, including NO_2. However, because Sentinel-5P measures total tropospheric NO_2 columns rather than ground-level concentrations, local ground-based validation remains essential to ensure the accuracy and applicability of the results.

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