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Analyzing Nitrogen Dioxide at Peninsular Malaysia Ports and Its Exclusive Economic Zone (EEZ) in 2023 Using Sentinel-5P Satellite

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ABSTRACT

The rise in nitrogen dioxide (NO_2) emissions, driven primarily by both land and sea transport, has become a major contributor to worsening air pollution. This study examines NO_2 pollution levels at major ports in Peninsular Malaysia and its Exclusive Economic Zone in 2023, utilizing data from the Sentinel-5P satellite. The Tropospheric Monitoring Instrument aboard Sentinel-5P offers high-resolution atmospheric measurements, enabling comprehensive spatial and temporal analysis of NO_2 concentrations across the region. Ground-based air quality data from the Department of Environment serve as a reference for validating satellite data. The study employs interpolation techniques, such as Inverse Distance Weighted, to visualize NO_2 distribution and assess its correlations with geographical and demographic factors. The findings reveal a significant increase in NO_2 levels, particularly in key maritime hubs, underscoring the urgent need for stricter regulatory measures and the adoption of sustainable transportation practices. This research not only supports Malaysia's ongoing air pollution monitoring efforts but also aligns with the nation's commitment to the International Maritime Organization's target of achieving net-zero emissions by 2050. By leveraging advanced satellite technology, this study contributes to improving air quality management and informing policy decisions aimed at reducing NO_2 emissions across the region.

Keywords: Air pollution, Malaysia ports, Nitrogen dioxide, Sentinel-5P, TROPOMI.

1. INTRODUCTION

Air pollution is shaped by factors such as urban form, economic growth, political conditions and social characteristics [1]. Nitrogen dioxide (NO_2), a reddish-brown gas [2] is one of the most prominent pollutants. It primarily results from the burning of fossil fuels in transportation, power plants, and industries [3]. NO_2 is considered highly hazardous to human health [4]. Emissions stem from both natural sources, such as soil-related processes and lightning strikes and man-made activities like vehicle exhaust and power generation [5]. Major contributors to NO_2 pollution include industrial fuel use, coal and gas combustion, vehicle emissions, biomass burning and power generation [6]. Past research indicates that the Movement Control Order between 2019 and 2021 led to lower emissions and improved air quality [7]. The Air Pollution Index in Klang has significantly worsened, rising from 62.70 in 2021 to 96 in 2023. Sentinel-5P satellite data further highlights the alarming rise in NO_2 concentrations at key Malaysian ports, signaling the need for urgent attention.

Both land and sea transport contribute significantly to NO_2 emissions, particularly near ports. While ports are vital for international trade and the flow of commodities, including essential goods such as food and electronics, they also contribute significantly to air pollution. Fossil fuel

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combustion is the primary source of emissions. Trucks powered by diesel and ships using heavy fuel oil release large quantities of carbon dioxide, sulfur oxides, nitrogen oxides and greenhouse gases (GHGs). Nearly four-fifths of global trade is carried by sea, which accounts for about 3% of global GHGs, as well as harmful pollutants like sulfur oxides, nitrogen oxides and particulate matter [8]. In urban areas, road transportation contributes over 25% of NO_x emissions [9]. The oxidation of nitric oxide, largely from traffic, produces the majority of NO_2 emissions in outdoor urban environments [10]. Ships, fueled by low-grade oils with high nitrogen content, release significantly higher NO_2 levels at sea. Increased NO_2 levels will continue to emerge from land and sea transport, as well as coal, gasoline and natural gas combustion in the energy sector [11]. In port areas, trucks and ships are the primary sources of NO_2 emissions [12]. The combined pollution from both land and sea transport creates hotspots around ports, highways and industrial centers.

Malaysia ranks 38th globally in terms of air quality, placing it among the countries with the most severe air pollution [7]. The International Maritime Organization (IMO) has set an ambitious target of achieving zero emissions for international sea transport by 2050, marking a critical step toward mitigating climate change and improving air quality. For a cleaner, sustainable future, Malaysia must align its national strategies with international environmental standards. This study contributes to the IMO's goal of net-zero emissions by applying Sentinel-5P satellite imagery to assess NO_2 concentrations at major ports in Peninsular Malaysia and its Exclusive Economic Zone (EEZ) for 2023. The study objectives are to: (1) analyze NO_2 emissions at key ports in Peninsular Malaysia and its EEZ using Sentinel-5P data; (2) compare tropospheric NO_2 data from Sentinel-5P with ground-based air quality measurements from the Department of Environment (DOE); and (3) evaluate the relationship between topographic features, population density and NO_2 emissions at these ports and surrounding areas.

2. MATERIAL AND METHODS

This study employed remote sensing methods to assess air pollution levels. Remote sensing, combined with GIS, offers powerful tools for collecting, analyzing and managing spatial data about Earth's surface and its features without direct interaction [13]. The focus of the study was on major ports in Peninsular Malaysia and its EEZ. Key ports include Port Klang, Tanjung Pelepas, Johor Port, Penang Port, Tok Bali Supply Base, Kertih Port, Kemaman Port, Kuantan Port and Lumut Port. These ports handle substantial volumes of domestic shipping and international vessels, making them critical nodes in sea-borne trade. Port Klang and Port Panjang, along with Johor Port and PTP, form the backbone of Malaysia's international trade, situated in the southern part of the peninsula [14]. Container throughput and ship calls at major ports, including Port Klang, Penang Port, PTP, Kuantan Port and Johor Port, have been consistently rising each year [15].

The high volume of vessel movements, especially near the Malacca Strait at Penang Port and Port Klang, leads to significant NO_2 emissions. This is primarily due to the combustion of fossil fuels in ship engines [16]. For this study, the year 2023 was selected for analysis. Data from the Air Quality Index (AQI) reveals that PM2.5 concentrations in Malaysia increased from 19.4 $\mu g/m^3$ in 2021 to 22.5 $\mu g/m^3$ in 2023. This increase signifies that air pollution levels in Malaysia during this period were classified as "Unhealthy for Sensitive Groups" [7]. Malaysia ranked 38th globally in terms of air quality in 2023, reflecting the severity of the pollution problem. To process and analyze the data, tools such as Google Earth Pro, ArcGIS 10.8, Microsoft Excel and a laptop were used. The overall methodology is illustrated in the flowchart in Figure 1.

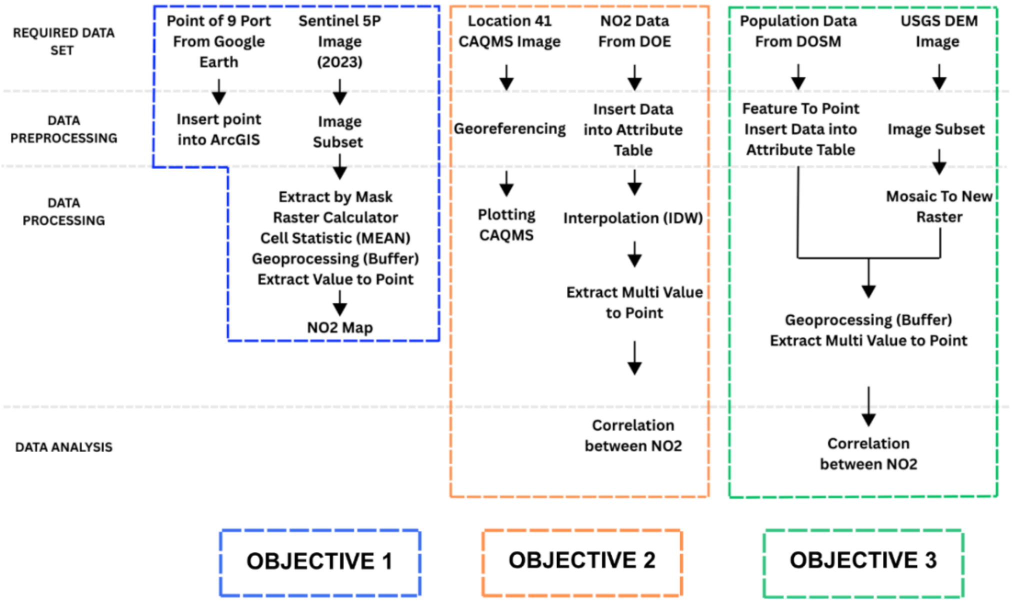

Figure 1: The flowchart of the overall methodology.

2.1 Required Data Set

The study requires several important data sets. This included Sentinel 5P images, ground-based data from the DOE, and other auxiliary data, such as topography, population, and the EEZ boundary of Peninsular Malaysia.

2.1.1 TROPOMI NO_2 Data

Sentinel-5P provides high-resolution atmospheric data for climate forecasting and air quality monitoring [17]. The Sentinel-5P satellite is equipped with a single payload instrument: TROPOMI (TROPOspheric Monitoring Instrument). The Copernicus Sentinel S5P satellite's single payload, TROPOMI, is a four-spectrometer system that measures the concentrations of different atmospheric species in the ultraviolet (UV), UV–visible (UV–VIS), near-infrared (NIR), and shortwave infrared (SWIR) spectral bands [18]. The selected wavelength enables the detection of emissions such as O_3, NO_2, CO, SO_2, CH_4, CH_2O and others [19]. TROPOMI is crucial for estimating human-caused emissions and for developing future regulation-based air pollution strategies [20]. This paper uses the offline Level 2 NO_2 (S5P L2 NO_2) tropospheric column data for the period January 1, 2023, until December 31, 2023.

2.1.2 Ground NO_2 Data

The distribution of Continuous Air Quality Monitoring Stations (CAQMS) in the study area in Peninsular Malaysia is shown in Figure 2. The DOE introduced rules to reduce dangerous pollutants from factory and car fuels, helping safeguard air quality and reduce risks to people's health and the environment [21]. The study area comprises 41 air quality monitoring stations. Ground NO_2 data were collected daily, monthly, and yearly from the DOE website. The ground NO_2 data were acquired from January 1, 2023, to December 31, 2023. These data were used to compare tropospheric NO2 from Sentinel-5P with ground-based air quality station measurements. 41 air quality monitoring stations in Peninsular Malaysia were selected in this study, as shown in Figure 2 and Table 1.

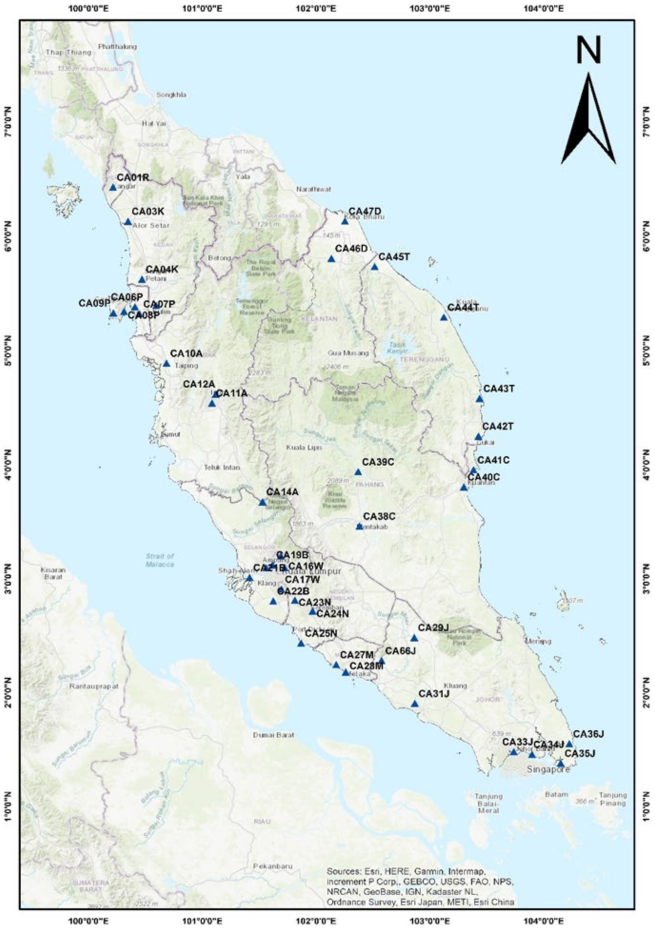

Figure 2: Location map of CAQMS in different regions in Peninsular Malaysia.

Table 1: List of CAQMS in Peninsular Malaysia.

STATION_ID	***LOCATION***
CA01R	Kangar, Perlis
CA03K	Alor Setar, Kedah
CA04K	Sungai Petani, Kedah
CA05K	Kulim Hi-Tech, Kedah
CA09P	Balik Pulau, Pulau Pinang
CA08P	Minden, Pulau Pinang
CA06P	Seberang Jaya, Pulau Pinang
CA07P	Seberang Perai, Pulau Pinang
CA10A	Taiping, Perak
CA12A	Tasek Ipoh, Perak
CA11A	Pegoh Ipoh, Perak
CA39C	Jerantut, Pahang
CA38C	Temerloh, Pahang
CA47D	Kota Bharu, Kelantan
CA46D	Tanah Merah, Kelantan
CA45T	Besut, Terengganu
CA44T	Kuala Terengganu, Terengganu
CA43T	Paka, Terengganu
CA42T	Kemaman, Terengganu
CA41C	Balok Baru Kuantan, Pahang
CA40C	Indera Mahkota Kuantan, Pahang
CA29J	Segamat, Johor
CA66J	Tangkak, Johor

Table 1: Continued.

CA31J	*Batu Pahat, Johor*
CA33J	Larkin, Johor
CA34J	Pasir Gudang, Johor
CA35J	Pengerang, Johor
CA36J	Kota Tinggi, Johor
CA28M	Bandaraya Melaka, Melaka
CA27M	Bukit Rambai, Melaka
CA25N	Port Dickson, Negeri Sembilan
CA24N	Seremban, Negeri Sembilan
CA23N	Nilai, Negeri Sembilan
CA22B	Banting, Selangor
CA17W	Putrajaya, W.P. Putrajaya
CA16W	Cheras, W.P. Kuala Lumpur
CA15W	Batu Muda, W.P. Kuala Lumpur
CA19B	Petaling Jaya, Selangor
CA20B	Shah Alam, Selangor
CA21B	Klang, Selangor
CA14A	Tanjung Malim, Perak

2.1.3 Auxiliary Data

The geographic boundaries of Peninsular Malaysia and its EEZ were obtained from the DIVA-GIS website and processed in ArcGIS. Furthermore, data on topography and population density in major port areas of Peninsular Malaysia will also be collected as input variables to explore the relationships among topographic features, population levels, and NO_2 concentrations. DEM data used in this study is the Shuttle Radar Topography Mission (SRTM) 1 Arc-Second Global data downloaded from the USGS website. The population data of Peninsular Malaysia was obtained from the Department of Statistics Malaysia (DOSM) website.

2.2 Data Preprocessing

TROPOMI NO_2 raster was subset to fit the study area of Peninsular Malaysia and its EEZ. Ground-monitored NO_2 concentrations in this study are from daily, monthly and yearly data provided by the DOE. The locations of all CAQMS in Peninsular Malaysia were plotted as shown in Figure 2, and the Excel data were added to the attribute table of the CAQMS points. SRTM DEM raster was then downloaded and subset to match the study area. Population data for Peninsular Malaysia were obtained from DOSM in Excel format, cleaned, and matched to the state names in the spatial dataset. A centroid point for each state was generated using the ‘Feature to Point’ tool in ArcGIS based on the state boundary shapefile, and the cleaned population data was joined to the centroid layer by state name, preparing the spatial and attribute data for further analysis.

2.3 Data Processing

After downloading the raw NO_2 data from Sentinel-5P in TIFF format, the data were imported into ArcGIS to initiate the processing. The first step involved extracting the relevant data for the study area boundary using the “Extract by Mask” tool. Next, the Raster Calculator was used to remove negative values from the raw NO_2 data. After all the daily NO_2 data for each month were prepared, the mean values were calculated using the Cell Statistics tool. Following that, the Geoprocessing “Buffer” tool was used to create polygons or zones around port locations for a 15 km distance. All raw DEM data downloaded from the USGS website were added to ArcGIS. The “Mosaic To New Raster” step was used to merge multiple raster datasets into a new raster dataset.

2.4 Data Analysis

A comparison of satellite- and ground-based NO_2 data was part of the analysis. A comparison was conducted to test how well satellite measurements could be made. To map continuous areas of NO_2 concentration within the study area, interpolation methods, in particular Inverse Distance Weighting (IDW), were applied to the CAQMS point data. It is used to predict values at all locations where no data are available [22]. Now that the IDW step has been performed, the next tool that will allow the comparison of NO_2 concentrations between ground-based and satellite-based measurements is the "Extract Multi Values to Points" tool. To explore how NO_2 emission concentrations are related to the other two variables, a similar procedure shall be carried out, extracting multivariate data and forming a scatter plot of the correlation. The 'Extract Multi Values to Points' tool was applied to extract the raster information, including Digital Elevation Model (DEM), population density and mean values from satellite-based NO_2 concentrations, into the centroids of the points that represent the states. After that, we will prepare a scatter plot to see correlations between variables in Excel.

3. RESULTS AND DISCUSSION

3.1 NO_2 Emission Patterns at Major Ports and EEZ of Peninsular Malaysia Based on Sentinel-5P Satellite Data

Figure 3 illustrates the boundary of the EEZ and the locations of nine major ports, along with the annual average distribution of tropospheric NO_2 concentrations across Peninsular Malaysia for 2023. The busiest seaports, including Port Klang, Port of Tanjung Pelepas, Johor Port and Penang Port, exhibit higher concentrations of NO_2. These elevated levels reflect significant emissions from ship traffic, cargo handling and port-based industrial operations. Moderate NO_2 concentrations are observed in surrounding areas, attributable to extensive road transport networks, including trucks and other logistics activities. The spatial distribution of NO_2 pollution correlates with port locations, highlighting the combined impact of land and sea transport on local air quality. This finding reinforces the study's hypothesis that NO_2 emissions are heavily influenced by the integration of maritime and land transportation systems. Figure 4 compares the tropospheric NO_2 column levels across the nine major ports in Peninsular Malaysia for 2023.

3.2 Accuracy of tropospheric NO_2 column extracted from Sentinel-5P with the ground-based

Figure 5 presents a scatter plot that demonstrates the relationship between ground-based NO_2 concentrations (ppm) obtained from CAQMS and the Tropospheric NO_2 column (mol/m^2) calculated from Sentinel-5P satellite images for 2023. This comparison assesses the suitability of Sentinel-5P data for scientific and air quality studies and evaluates its alignment with ground-based data. The trend line equation ($y = 0.006x - 2E\text{-}07$) and the coefficient of determination ($R^2 = 0.757$) indicate a strong positive correlation between the two datasets. This suggests that satellite observations provide a reliable estimate of surface NO_2 concentrations.

Several factors, including atmospheric conditions, satellite overpass time, spatial averaging, and differences in data retrieval methods, could account for discrepancies between ground-based and satellite observations. Despite these limitations, the relatively high value of the coefficient of determination (R^2) confirms that Sentinel-5P data is suitable for scientific investigations, long-term trend analysis and regional air quality monitoring, especially in areas lacking ground-based monitoring networks.

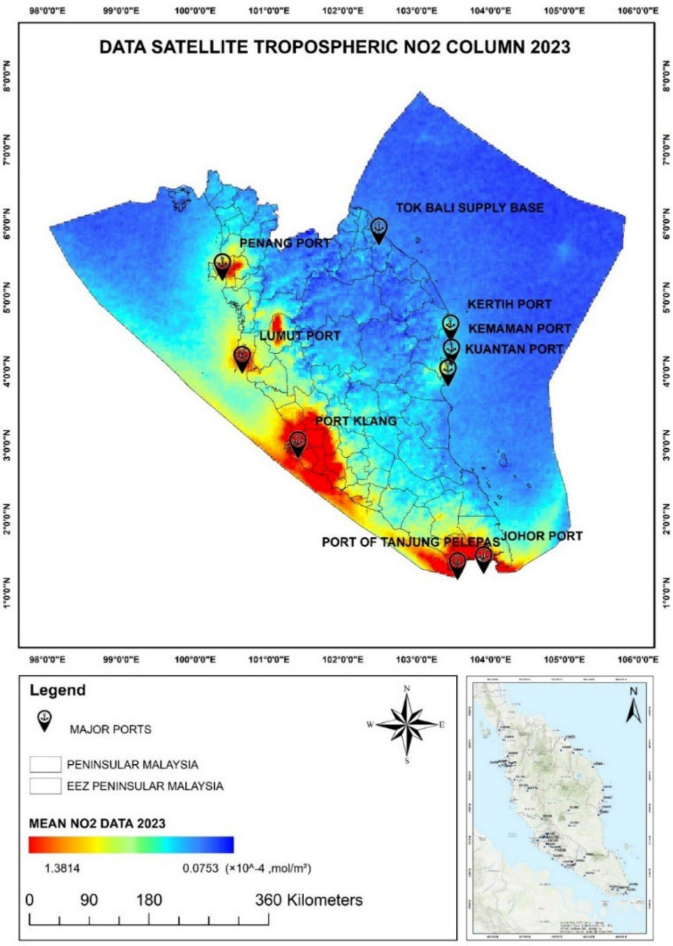

Figure 3: Annual Tropospheric NO_2 Concentration and Major Port Locations in Peninsular Malaysia (2023).

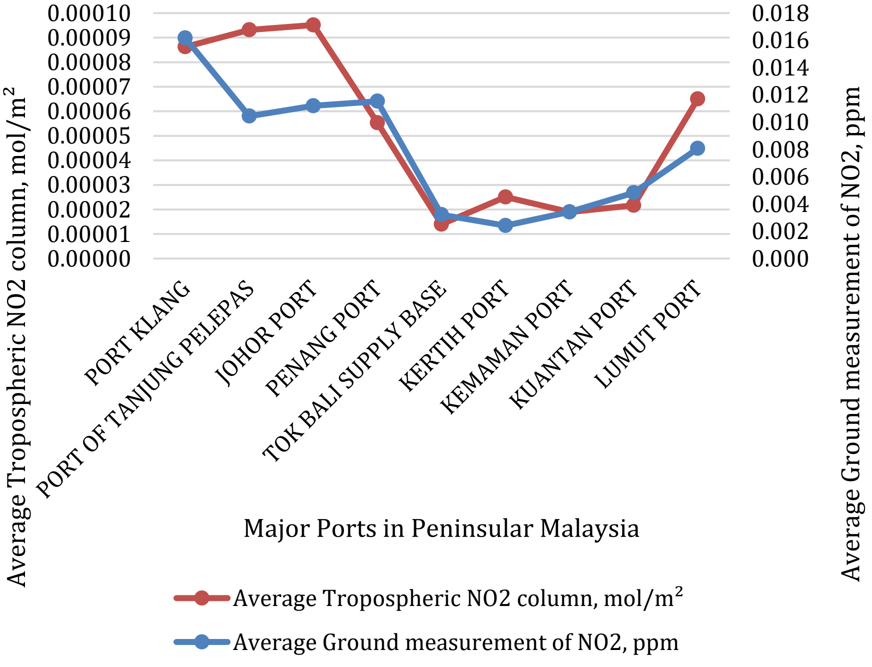

Figure 4: Comparison of tropospheric NO_2 column at 9 major ports in Peninsular Malaysia (2023).

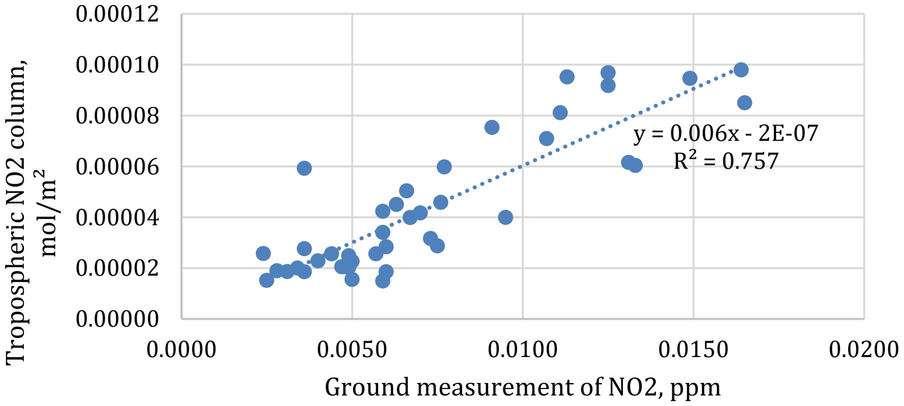

Figure 5: Comparison of tropospheric NO_2 column at 9 major ports in Peninsular Malaysia (2023).

3.3 Relationship Between NO_2 Pollutants, Geographical and Demographical Data

This study employs statistical analyses to explore the relationship between NO_2 concentrations and geographical and demographic data through the calculation of correlation coefficients. The correlation values between NO_2 and the geographical and demographic data are presented in Figures 6, 7, 8, and 9. The analysis supports the hypothesis that higher altitudes are linked to lower NO_2 concentrations, as indicated by the weak negative correlation between elevation and both ground-level and tropospheric NO_2. Previous studies have shown that elevation influences air pollution levels, with NO_2 and CO concentrations typically lower at higher elevations and increasing as elevation decreases [23]. This suggests that NO_2 pollutants accumulate more in low-lying areas, likely due to atmospheric dispersion and deposition processes.

The strong positive correlation between NO_2 and population density indicates that areas with higher population density experience more severe NO_2 pollution. Human activities, such as transportation and industrial emissions, significantly contribute to this correlation. The analysis reveals that population density has a slight correlation with ground-level NO_2 but a stronger correlation with tropospheric NO_2, highlighting the impact of human activities on air quality at different atmospheric levels.

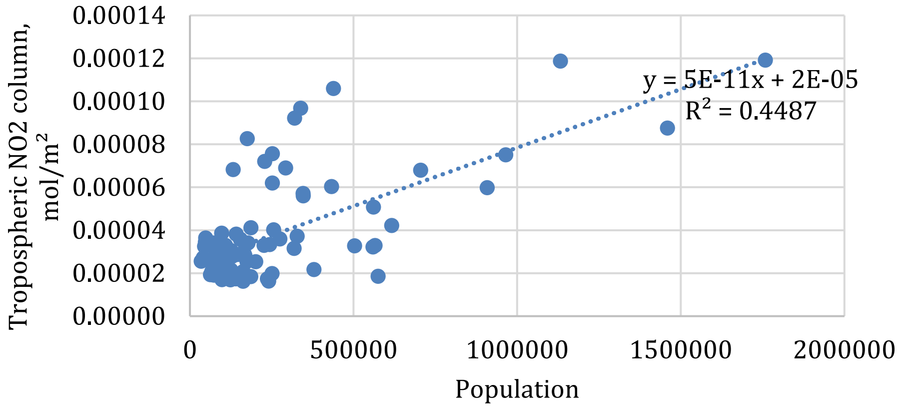

Figure 6: Graph correlation values between tropospheric NO_2 and demographic data.

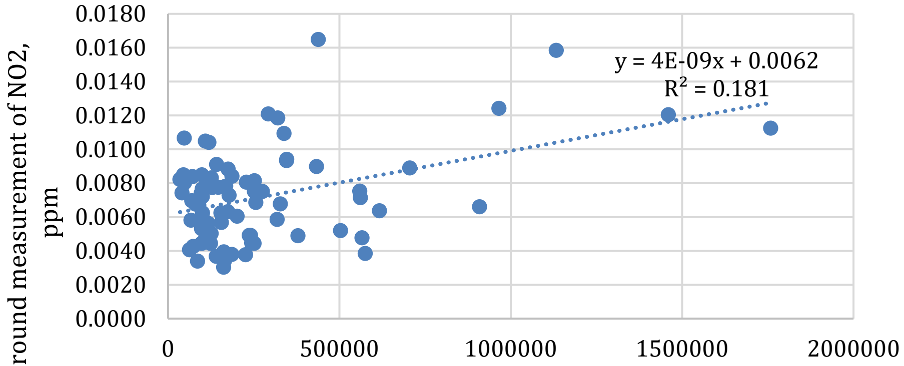

Figure 7: Graph correlation values between ground NO_2 and demographic data.

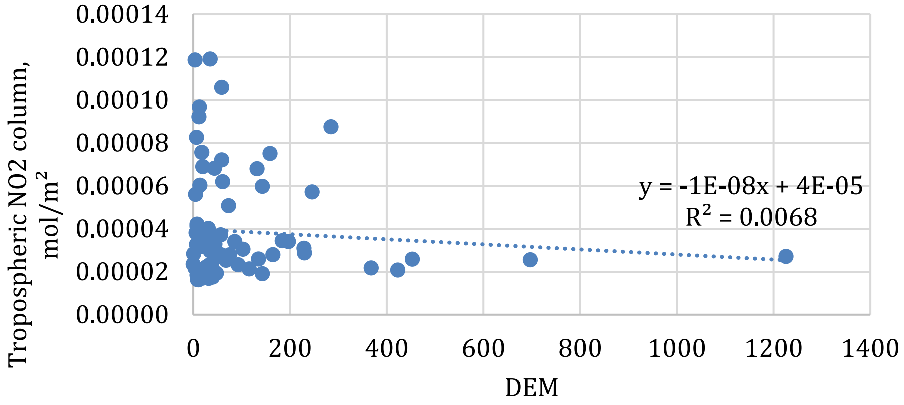

Figure 8: Graph correlation values between tropospheric NO_2 and geographical data.

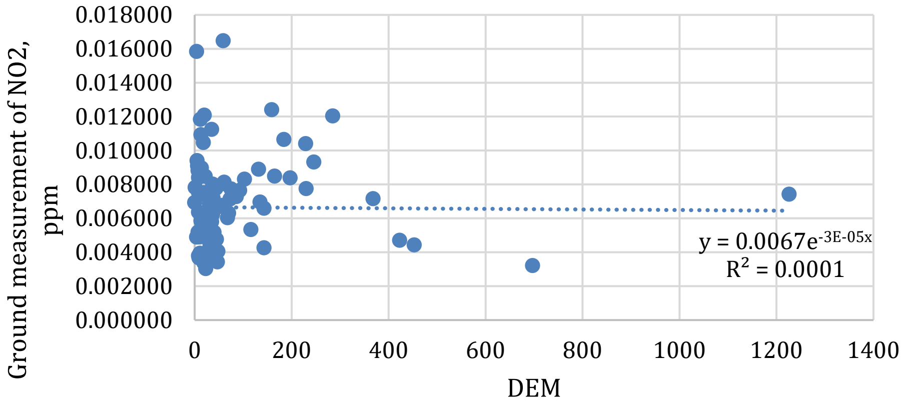

Figure 9: Graph correlation values between ground NO_2 and geographical data.

4. CONCLUSION

This research successfully analyzed the concentration and distribution of NO_2 emissions in major seaports and the EEZ of Peninsular Malaysia using Sentinel-5P satellite data for 2023. Geospatial analysis techniques, including buffer analysis, IDW interpolation, and multi-value extraction, were applied to identify emission patterns at key traffic gateways, such as Port Klang, Johor Port, and the Port of Tanjung Pelepas. The findings confirm that the primary sources of NO_2 emissions in these regions are land and sea transportation. Overlaying topographical and demographic data revealed that areas with lower elevations and higher population densities are more vulnerable to elevated NO_2 concentrations. To mitigate these issues, stricter port emission regulations are recommended, in alignment with the IMO target of achieving net-zero emissions by 2050. Solutions include adopting cleaner fuels, energy-efficient ships, onshore power for berthed vessels and enhanced remote sensing monitoring. These measures not only support Malaysia's commitment to sustainable maritime development but also strengthen its position in regional trade.

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