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Satellite-Based Assessment of Nitrogen Dioxide Emissions from Libyan Power Plants: 2023 Annual Analysis

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Abstract

Nitrogen dioxide (NO_2) is a major atmospheric pollutant with severe implications for human health and the environment. This study utilizes the TROPOspheric Monitoring Instrument (TROPOMI) aboard the Sentinel-5P satellite, accessed via Google Earth Engine (GEE), to analyse NO_2 levels across Libya during 2023. The analysis reveals significant spatial and temporal variations in NO_2 vertical column densities, identifying power plants in urban hubs such as Tripoli, Benghazi, and Misrata as primary emission sources. Seasonal trends show a marked elevation in pollution during the summer, with concentrations peaking in June at 7.01×10^{-5} (mol/m^2), representing an 18.4% increase relative to the annual mean. These spikes are driven by increased energy demand, enhanced photochemical reactions, and meteorological conditions. The findings emphasize the critical need for targeted interventions, specifically recommending the retrofitting of power plants with selective catalytic reduction (SCR) systems and the diversification of the energy portfolio through investment in solar and wind infrastructure to reduce fossil fuel dependence.

Keywords: Nitrogen dioxide, TROPOMI, Sentinel-5P, Google Earth Engine, Libya, air quality, satellite monitoring, power plants, seasonal variation.

التقييم المعتمد على بيانات الأقمار الصناعية لانبعاثات ثاني أكسيد النيتروجين من محطات توليد الطاقة في ليبيا: تحليل سنوي لعام 2023

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الملخص

يُعد ثاني أكسيد النيتروجين (NO_2) أحد الملوثات الجوية الرئيسة لما له من آثار خطيرة على صحة الإنسان والبيئة. تهدف هذه الدراسة إلى تحليل مستويات ثاني أكسيد النيتروجين في أنحاء ليبيا خلال عام 2023 باستخدام بيانات أداة رصد التروبوسفير (TROPOMI) المحمولة على القمر الصناعي Sentinel-5P ، وذلك عبر منصة Google Earth Engine (GEE). أظهرت نتائج التحليل وجود تباينات مكانية وزمانية واضحة في كثافات العمود الرأسي لثاني أكسيد النيتروجين، حيث تم تحديد محطات توليد الطاقة الواقعة في المراكز الحضرية الكبرى مثل طرابلس وبنغازي ومصراتة بوصفها المصادر الرئيسة للانبعاثات. كما بيّنت النتائج وجود نمط موسمي يتمثل في ارتفاع ملحوظ في مستويات التلوث خلال فصل الصيف، إذ بلغت ذروة التركيز في شهر يونيو قيمة قدرها 7.01×10^{-5} مول/م^2، مسجلة زيادة بنسبة 18.4% مقارنة بالمتوسط السنوي. ويُعزى هذا الارتفاع إلى زيادة الطلب على الطاقة، وتعزز التفاعلات الضوئية الكيميائية، إضافة إلى العوامل الجوية السائدة. وتؤكد هذه النتائج الحاجة الملحّة إلى اتخاذ إجراءات موجهة للحد من الانبعاثات، مع التوصية بتحديث محطات توليد الطاقة عبر تركيب أنظمة الاختزال التحفيزي الانتقائي(SCR) ، إلى جانب تنويع مصادر الطاقة من خلال الاستثمار في مصادر الطاقة الشمسية وطاقة الرياح للحد من الاعتماد على الوقود الأحفوري.

الكلمات المفتاحية: ثاني أكسيد النيتروجين، الرصد بالأقمار الصناعية، محطات توليد الطاقة.

1. Introduction

Nitrogen dioxide (NO_2) is a major atmospheric pollutant with severe implications for human health and the environment. The United States Environmental Protection Agency (EPA) has identified nitrogen oxides, along with sulphur oxides, carbon monoxide, ozone (O_3), and particulate matter (PM_{10}), as key indicators of air quality (U.S. EPA, 2023).Emitted primarily from fossil fuel combustion in vehicles, power plants, and industrial processes, NO_2 contributes to the formation of ground-level ozone and particulate matter, exacerbating air quality issues. Monitoring NO_2 concentrations is crucial for assessing air quality trends, ensuring regulatory compliance, and developing effective pollution control strategies (Sameh et al., 2023).

Libya, a North African country with significant oil and gas resources, faces unique air quality challenges due to its industrial activities, urbanization, and climatic conditions. The country's heavy reliance on fossil fuels for energy generation, coupled with limited environmental monitoring infrastructure, necessitates innovative approaches to assess air pollution levels. Traditional ground-based monitoring networks are sparse and often inadequate for comprehensive coverage of Libya's vast territory (Ashokri et al., 2022).

Satellite remote sensing offers a powerful alternative for monitoring atmospheric pollutants over large geographic areas with consistent temporal coverage. The TROPOspheric Monitoring Instrument (TROPOMI) aboard the Sentinel-5P satellite provides high-resolution observations of trace gases, including NO_2, with unprecedented spatial detail(Rahman et al., 2025). By leveraging advanced satellite data processing capabilities within the Google Earth Engine (GEE) platform, this research offers a comprehensive overview of nitrogen dioxide pollution patterns in Libya, contributing to our understanding of air quality dynamics in the region.

2. Literature Review

2.1 Satellite Monitoring of NO_2

Satellite-based remote sensing has revolutionized atmospheric monitoring by providing global coverage and consistent temporal observations. The TROPOMI instrument, launched in 2017, represents a significant advancement in satellite-based atmospheric composition monitoring. With its high spatial resolution of 3.5 × 5.5 km², TROPOMI enables detailed analysis of pollution sources and their spatial distribution(Veefkind et al., 2012). The instrument's enhanced capabilities have been extensively utilized for monitoring urban air quality, industrial emissions, and regional pollution patterns across various geographical regions.

2.2 NO_2 Monitoring in North Africa

North African countries face significant air quality challenges due to rapid urbanization, industrial growth, and unique meteorological conditions. Previous studies have documented elevated NO_2 concentrations in major North African cities, with variations linked to local emission sources and seasonal meteorological patterns (Doumbia et al., 2021; Salama et al., 2022). The regional climate, characterized by high temperatures and low precipitation, can exacerbate photochemical processes that contribute to secondary pollutant formation. Understanding these regional dynamics is essential for effective air quality management strategies. The region's limited air quality monitoring infrastructure makes satellite-based observations particularly valuable for assessing pollution patterns and informing policy decisions.

2.3 Use of Google Earth Engine in Air Quality Studies

Google Earth Engine has emerged as a powerful cloud-computing platform for processing and analysing large-scale geospatial datasets, including satellite observations of atmospheric composition. The platform's computational capabilities enable researchers to process multi-year satellite datasets efficiently, facilitating comprehensive temporal and spatial analysis of air pollution patterns (Gorelick et al., 2017).Recent applications have demonstrated the effectiveness of GEE for monitoring air quality changes, identifying pollution hotspots, and supporting environmental decision-making processes (Adon et al., 2016) (Halder et al., 2023) (Lelieveld et al., 2015).

2.4 Air Quality in Libya

Limited research has been conducted on air quality conditions in Libya, primarily due to political instability and infrastructure challenges. A comprehensive inventory by Nassar et al. (2017) identified that Libya's annual air emissions total approximately 61.1 million tonnes, with the electricity industry contributing 33.9% of total emissions, followed by transportation (30.7%), residential and commercial sectors (14.2%), and cement manufacturing (10.9%). Specifically for nitrogen oxides, the transportation sector is the dominant source (47%), followed by the electricity sector (21.3%). The country's extensive oil and gas infrastructure, combined with rapid urbanization and limited environmental regulations, creates conditions conducive to elevated pollutant concentrations. Previous studies have identified major urban centers such as Tripoli, Benghazi, and Misrata as potential pollution hotspots, with power generation facilities contributing significantly to atmospheric NO_x emissions (Ashokri et al., 2022; Nassar et al., 2017). Understanding

Libya's air quality status is crucial for protecting public health, as hospitals have reported increased strain from acute and chronic respiratory diseases associated with air pollution (Nassar et al., 2017), and for supporting sustainable development goals

3. Methodology

This study employs satellite-based remote sensing techniques to analyse nitrogen dioxide pollution patterns across Libya during 2023. The methodology combines TROPOMI satellite observations with Google Earth Engine's cloud computing capabilities to process and analyse large-scale atmospheric datasets.

Data acquisition utilized the Sentinel-5P TROPOMI Level 2 NO_2 tropospheric column products, which provide daily global coverage with a spatial resolution of approximately 3.5 × 5.5 km^2. Specifically, the data were accessed via the Google Earth Engine platform using the collection identifier COPERNICUS/S5P/OFFL/L3_NO2, enabling efficient processing of the extensive temporal dataset covering the entire year 2023.

Spatial analysis focused on identifying regions with elevated NO_2 concentrations, with particular attention to areas surrounding major power generation facilities, urban centers, and industrial zones. Geographic information systems (GIS) techniques were employed to overlay NO_2 concentration maps with infrastructure datasets to assess the relationship between emission sources and pollution patterns.

Temporal analysis examined monthly and seasonal variations in NO_2 concentrations throughout 2023. Statistical analysis techniques were applied to identify significant trends and patterns in the temporal dataset. Meteorological factors influencing NO_2 concentrations, including temperature, wind patterns, and seasonal variations, were considered in the interpretation of results.

Data quality control procedures were implemented following TROPOMI best practices. Only observations with qa value > 0.75 were retained to ensure data reliability. Cloud-screened pixels and observations with solar zenith angles > 70° were excluded from the analysis to minimize retrieval uncertainties(Yu et al., 2025).

4. Results and Discussion

4.1 Nitrogen Dioxide Concentrations around Power Plants

Our analysis revealed that power plants are significant contributors to elevated nitrogen dioxide (NO_2) levels in Libya. The spatial distribution of NO_2 concentrations showed markedly higher values in regions hosting power plants compared to areas without major energy generation facilities. This pattern is consistent with the known emission characteristics of fossil fuel-powered electricity generation, where high-temperature combustion processes produce substantial quantities of nitrogen oxides(Mohieldeen et al., 2024).

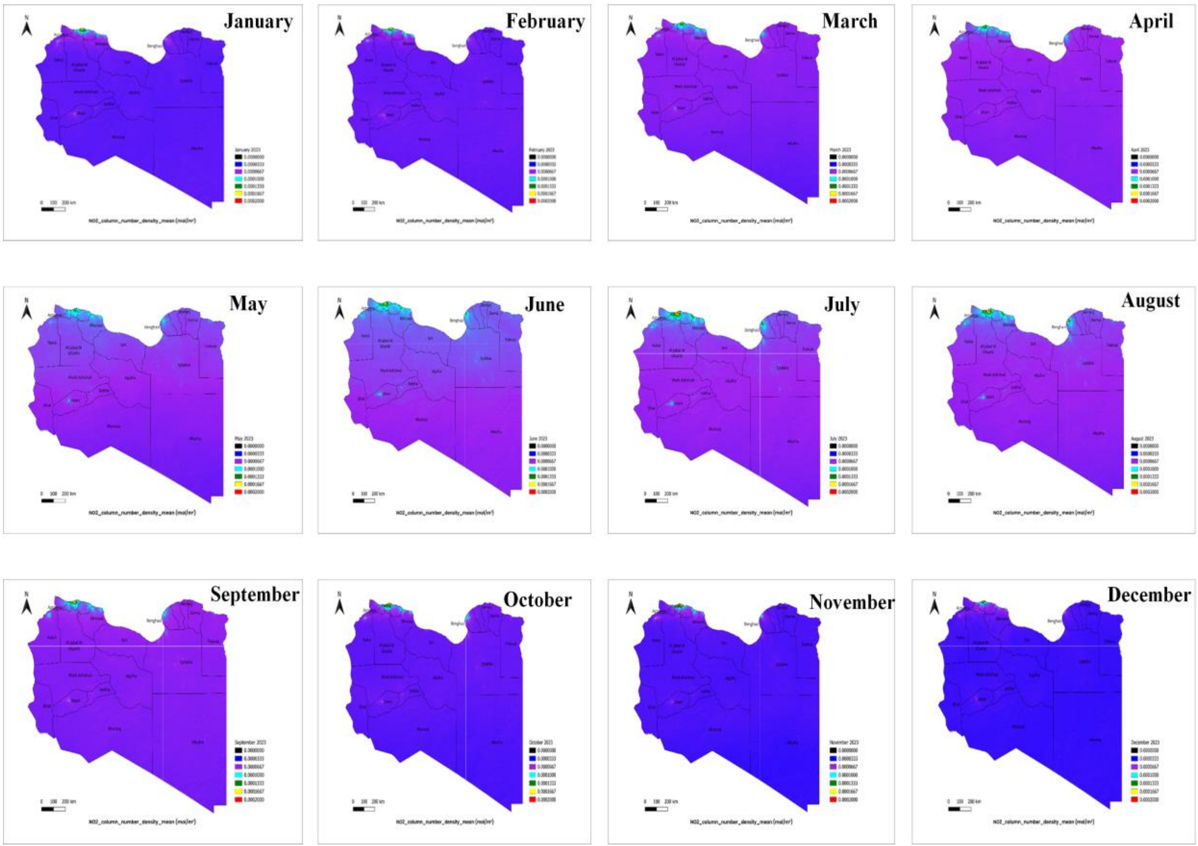

Figure 1: Spatial distribution of monthly vertical column densities of NO_2 in Libya during the period Jan 2023 to Dec 2023.

Regions such as Tripoli, Benghazi, and Misrata exhibited the highest levels of NO_2, corresponding to the dense clustering of power generation facilities in these areas, as shown in Figure 1. The concentration gradients observed around these facilities typically showed peak values directly over the power plants, with gradual decrease in surrounding areas, indicating the localized nature of these emission sources. This spatial pattern provides strong evidence for the role of power generation as a primary contributor to atmospheric NO_2 in Libya.

The analysis also revealed that the impact of power plant emissions extends beyond the immediate vicinity of the facilities. Downwind areas showed elevated NO_2 concentrations that could be traced back to major power generation sites, suggesting regional transport of pollutants. This finding has important implications for air quality management, as it indicates that emission control strategies must consider both local and regional effects of major point sources.

4.2 Seasonal Variations in NO_2 Levels

The temporal analysis of NO_2 concentrations throughout 2023 revealed significant seasonal variations, with notably higher levels during the summer months, as shown in table 1 and figure 2. This seasonal trend can be attributed to several factors that collectively contribute to elevated atmospheric NO_2 concentrations during the warmer period of the year.

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Volume 9 - Issue 18 المجلد 9 - العدد 18

Table 1: Monthly average NO_2 vertical column densities in Libya during 2023, with values relative to the annual mean.

Month	NO_2 Concentration (mol/m²)	NO_2 Concentration (molecule/cm²)	Relative to Annual Mean (%)
January	5.21×10^{-5}	3.14×10^{15}	-12.0%
February	5.48×10^{-5}	3.30×10^{15}	-7.4%
March	6.04×10^{-5}	3.64×10^{15}	+2.0%
April	6.33×10^{-5}	3.81×10^{15}	+6.9%
May	6.67×10^{-5}	4.02×10^{15}	+12.7%
June	7.01×10^{-5}	4.22×10^{15}	+18.4%
July	6.99×10^{-5}	4.21×10^{15}	+18.1%
August	6.68×10^{-5}	4.02×10^{15}	+12.8%
September	6.12×10^{-5}	3.68×10^{15}	+3.4%
October	5.30×10^{-5}	3.19×10^{15}	-10.5%
November	4.84×10^{-5}	2.91×10^{15}	-18.2%
December	4.55×10^{-5}	2.74×10^{15}	-23.1%

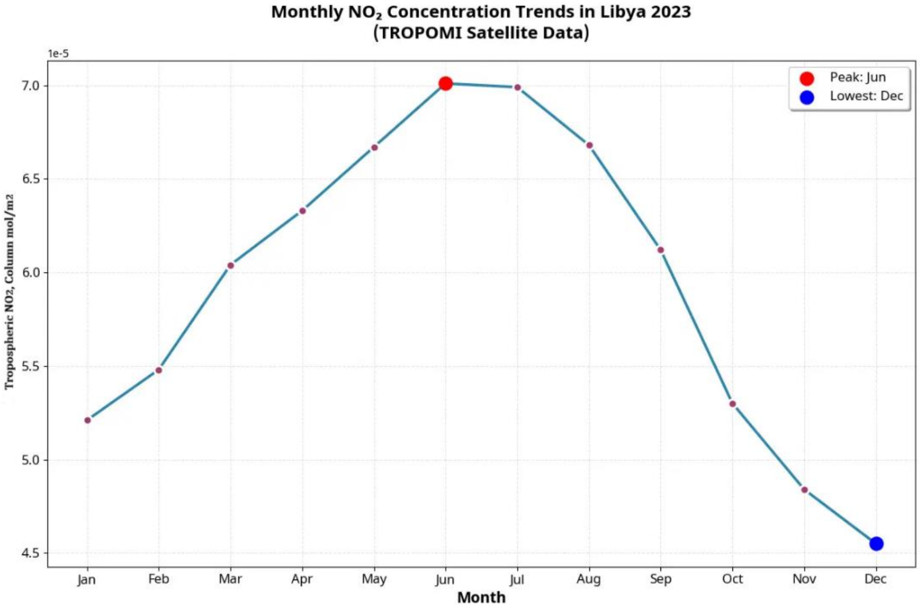

Figure 2: Monthly variation of NO_2 vertical column densities in Libya during 2023, based on TROPOMI satellite data.

Increased Energy Demand: The summer months in Libya are characterized by extremely high temperatures, leading to increased electricity demand for air conditioning and cooling systems. This heightened energy consumption results in greater power plant operations and, consequently, higher NO_2 emissions from fossil fuel combustion processes(Lange et al., 2022).

Photochemical Reactions: Higher temperatures during summer months enhance photochemical reaction rates in the atmosphere. These conditions promote the formation of NO_2 through photochemical processes and can lead to the accumulation of nitrogen oxides in the atmospheric boundary layer (Rey-Pommier et al., 2022).The intense solar radiation characteristic of Libya's climate provides optimal conditions for these photochemical transformations.

Meteorological Conditions: Summer meteorological patterns in Libya, including reduced wind speeds and atmospheric mixing, can contribute to the accumulation of pollutants near emission sources. The stable atmospheric conditions typical of summer months reduce the dispersion of NO_2, leading to higher local concentrations compared to other seasons when atmospheric mixing is more efficient. Similar findings for this seasonal pattern align with other studies in Mediterranean and Middle Eastern regions (Ashokri et al., 2022; Rabiei-Dastjerdi et al., 2022).

The seasonal analysis also revealed that winter months showed relatively lower NO_2 concentrations, likely due to reduced energy demand for cooling, improved atmospheric dispersion conditions, and lower rates of photochemical NO_2 formation. This seasonal pattern is crucial for understanding the temporal dynamics of air pollution in Libya and has important implications for public health protection strategies.

4.3 Implications for Air Quality Management

The findings from this comprehensive analysis have significant implications for air quality management and environmental policy development in Libya. The identification of power plants as primary sources of NO_2 pollution provides a clear focus for targeted emission reduction strategies.

The elevated NO_2 concentrations observed in this study have significant public health implications. Long-term exposure to NO_2 has been associated with increased cardiovascular and respiratory mortality, with studies showing a 4% increase in cardiovascular mortality risk per 10 $\mu g/m^3$ increase in NO_2 levels(Hoek et al., 2013; Meng et al., 2021) .The persistently high concentrations in Tripoli, Benghazi, and Misrata suggest that populations in these urban centers may face elevated health risks, particularly during summer months when NO_2 levels peak.

The spatial analysis results suggest that implementing stricter emission standards for power generation facilities could yield substantial improvements in regional air quality. Priority should be given to retrofitting existing power plants with advanced emission control technologies, such as selective catalytic reduction (SCR) systems, which can significantly reduce NO_2 emissions from combustion processes (Loho et al., 2025).

The seasonal variation patterns observed in this study indicate that air quality management strategies should be adapted to account for temporal variations in pollution levels. During summer months, when NO_2 concentrations are typically highest, enhanced monitoring and potentially temporary restrictions on high-emission activities could help protect public health.

The comprehensive spatial coverage provided by satellite monitoring demonstrates the value of remote sensing technologies for air quality assessment in regions with limited ground-based monitoring infrastructure. Libya should consider integrating satellite-based observations into its environmental monitoring framework to complement existing ground-based measurements and provide comprehensive coverage of the country's air quality status.

Long-term air quality improvement strategies should focus on diversifying Libya's energy portfolio to include cleaner renewable energy sources, which would reduce the country's dependence on fossil fuel-powered electricity generation. Investment in solar and wind energy infrastructure could significantly reduce NO_2 emissions while supporting sustainable economic development.

5. Conclusions

This study successfully demonstrated the application of satellite-based remote sensing for comprehensive analysis of nitrogen dioxide pollution patterns across Libya during 2023. The integration of TROPOMI observations with Google Earth Engine's computational capabilities provided unprecedented insights into the spatial and temporal dynamics of NO_2 concentrations throughout the country.

Key findings include the identification of power plants as primary contributors to elevated NO_2 levels, with major urban and industrial centers showing the highest concentrations. The observed seasonal variations, with peak levels during summer months, reflect the combined influence of increased energy demand, enhanced photochemical processes, and meteorological conditions characteristic of Libya's climate. The analysis revealed NO_2 vertical column densities ranging from 4.55×10^{-5} mol/m^2 in December to 7.01×10^{-5} mol/m^2 in June, representing a 54% increase from winter to summer peaks. Power plant regions showed NO_2 levels 2-3 times higher than background concentrations, with distinct spatial gradients extending 20-30 km downwind from major facilities.

A comparison with previous TROPOMI-based observations from 2021(Ashokri et al., 2022) reveals consistent spatial patterns of pollution hotspots but suggests potentially elevated NO_2 concentrations in 2023, with summer peak values approximately 46% higher than those observed in 2021. Furthermore, while this study identifies power plants as the primary emission sources, the 2021 study attributed the highest contribution to factors including vehicle ownership, industrialization, and urbanization. This difference may highlight a shift in emission patterns or a refinement in source attribution with more recent data. This temporal comparison underscores the importance of continued satellite-based monitoring for tracking Libya's air quality trends and evaluating the effectiveness of future emission reduction measures.

The research contributes valuable information for environmental policy development and air quality management strategies in Libya. The findings support the need for targeted emission reduction measures focused on power generation facilities, implementation of advanced emission control technologies, and development of comprehensive air quality monitoring networks.

Future research should expand the temporal scope of analysis to examine long-term trends and evaluate the effectiveness of emission reduction measures. Integration of additional satellite datasets and ground-based measurements would further enhance understanding of Libya's air quality dynamics and support evidence-based environmental management decisions. The methodological approach demonstrated in this study can be applied to other regions facing similar air quality challenges, contributing to global efforts to monitor and improve atmospheric environmental conditions through innovative remote sensing technologies.

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