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Air Quality Dynamics in the Vicinity of PT. Semen Padang, Padang City, Indonesia: Insights from Sentinel-5P Data During 2023

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This study aims to evaluate air quality in the vicinity of PT. Semen Padang, Padang City, West Sumatra, Indonesia, throughout 2023, utilizing data from the Copernicus Sentinel-5P satellite. The analysis reveals significant variations in the concentrations of pollutants such as carbon monoxide (CO), nitrogen dioxide (NO_2), sulfur dioxide (SO_2), and ozone (O_3). Higher pollutant concentrations were observed in urban areas, influenced by industrial activities and vehicular emissions. Levels of CO and O_3 frequently exceeded the World Health Organization (WHO) guidelines, posing potential health risks. Although most pollutant concentrations remained within safe limits, the findings underscore the importance of continuous air quality monitoring and the implementation of targeted mitigation measures to preserve environmental quality and safeguard public health, particularly in densely populated areas.
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Keywords: *air quality, pollutant, satellite monitoring, public health.*

1. INTRODUCTION

Air quality is a vital aspect of environmental health, particularly in urban and industrial areas where anthropogenic emissions are prevalent. Exposure to elevated levels of atmospheric pollutants—such as nitrogen dioxide (NO_2), carbon monoxide (CO), ozone (O_3), and sulfur dioxide (SO_2)—is strongly associated with increased risks of respiratory and cardiovascular diseases. The World Health Organization (WHO) has highlighted that poor air quality contributes to millions of premature deaths annually, especially in regions with limited air quality monitoring infrastructure (Omokpariola et al., 2024).

The development of satellite-based remote sensing has significantly improved the monitoring of atmospheric pollutants. The Sentinel-5P satellite, launched by the European Space Agency (ESA) under the Copernicus program, provides high-resolution, near real-time data on a wide range of atmospheric constituents. These data allow researchers to observe spatial distributions, detect pollution hotspots, and analyze seasonal trends with greater accuracy. Sentinel-5P imagery has also proven effective for assessing the vulnerability of densely populated areas to air pollution (Hassaan et al., 2023). In addition, recent studies have demonstrated that combining Sentinel-5P data with automated platforms such as Google Earth Engine enhances pollutant monitoring by offering reliable spatial coverage in developing regions (Garajeh et al., 2023).

In Indonesia, the cement industry is a notable contributor to air pollution due to the emission of particulate matter and nitrogen compounds. PT. Semen Padang, located in Padang, West Sumatra, is one of the country's oldest and largest cement manufacturing plants. Its industrial emissions, combined with increasing vehicular activity from urban growth in surrounding areas, present a potential risk to local air quality (Anggraini et al., 2020; Rahman et al., 2024).

This study aims to assess the spatial and temporal distribution of air pollutants in the vicinity of PT. Semen Padang throughout 2023 using Sentinel-5P data. By identifying key pollution patterns and

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seasonal variations, this research contributes to a better understanding of industrial air pollution dynamics in the region.

2. METHOD

2.1 Study Area

The study area is located in the city of Padang, West Sumatra, Indonesia. Padang covers an area of approximately 694.96 km² and is home to an estimated population of 1.01 million (2023). The study area was defined geographically within coordinates bounded by longitude 100.4205°E to 100.5070°E and latitude 0.9849°S to 0.9026°S (Figure 1). The city is a major economic center, with a diverse range of activities including agriculture, manufacturing, and tourism. It also serves as a hub for regional trade and transportation.

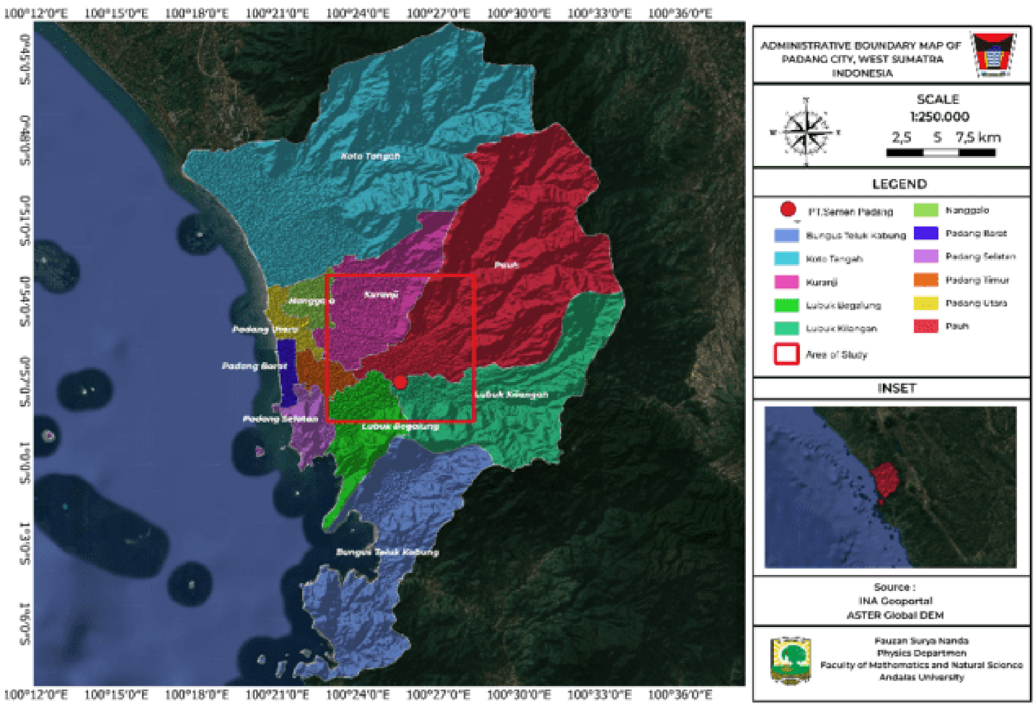


Figure 1 Study area and administrative boundary map developed by the authors using QGIS (Ver. 3.34.15).

2.2 Methodology

This study analyzed air quality around PT. Semen Padang using data from the Copernicus Sentinel-5P satellite, focusing on concentrations of carbon monoxide (CO), nitrogen dioxide (NO_2), sulfur dioxide (SO_2), and ozone (O_3) throughout 2023. The data was sourced from two platforms: the Copernicus Data Space Ecosystem, which provides Level 2 and Near Real-Time (NRTI) products, and Google Earth Engine (GEE), which offers preprocessed Level 2 products with global coverage. To improve the accuracy of the air quality data, machine learning models were employed to integrate meteorological and land-use parameters (Stirnberg et al., 2020).

2.3 Data Selection and Preprocessing

The Copernicus Data Space Ecosystem plays a pivotal role in facilitating the acquisition of air quality data, essential for effective monitoring and management. This study utilized Sentinel-5P data, focusing on three distinct months—January, May, and September 2023—to capture seasonal variations. Preprocessing steps, such as cloud fraction filtering with a threshold of 0.3 to exclude cloud-affected pixels, were applied to enhance data reliability, which is crucial for accurate air quality assessments (Sembiring et al., 2024). The integration of Google Earth Engine further supported the analysis by providing additional preprocessed data for comparison. The study employed Level 2 and Near Real-

Time (NRTI) products from Sentinel-5P to ensure high-quality atmospheric measurements, and monthly data aggregation enabled a comprehensive seasonal analysis. Reliable data is critical for data-driven decision-making in air quality monitoring systems, which are essential for effective policymaking (Sembiring et al., 2024). Moreover, comprehensive databases like the Brazilian Atmospheric Inventories (BRAIN) contribute to enhancing air quality management efforts (Hoinaski et al., 2023). However, despite advancements in data processing techniques, challenges such as data scarcity in certain regions remain a significant obstacle to effective air quality monitoring and policy implementation.

2.4 Data Processing and Analysis

The analysis focused on identifying temporal trends and spatial distributions of the pollutants. Monthly average concentrations of CO, NO_2, SO_2, and O_3 were calculated for both datasets to evaluate pollutant variability throughout the year (Figure 2). Spatial distribution maps of average pollutant concentrations were generated to highlight areas with elevated levels. Outputs from the Copernicus Data Space Ecosystem and GEE were compared to assess consistency, using statistical metrics such as percentage differences and correlations to evaluate agreement between the two datasets.

For data processing, Python was used within Visual Studio Code to handle and process NetCDF data, a common format for satellite data, allowing for efficient manipulation and analysis of the air quality parameters. Google Earth Engine (GEE) was employed for processing and analyzing GeoTIFF data, which includes preprocessed satellite imagery that was used to further assess pollutant concentrations. The integration of both tools provided a comprehensive approach to data handling and analysis.

The spatial and temporal results were visualized through maps and charts, representing trends and variations across the study area and facilitating a straightforward comparison between the datasets. This methodology provides a comprehensive assessment of air quality in the study area by leveraging multiple data sources for Sentinel-5P products. The comparison between Copernicus Data Space Ecosystem and GEE highlights potential variations due to data preprocessing approaches, ensuring the robustness of the findings.

3. RESULTS AND DISCUSSION

The air quality assessment for 2023, utilizing Sentinel-5P satellite data, reveals distinct spatial and temporal distribution patterns for major atmospheric pollutants, with each gas exhibiting unique characteristics influenced by industrial and urban sources.

Figure 2 The Monthly Mean Value for CO, NO2 O3 and SO2.

3.1 Carbon monoxide (CO)

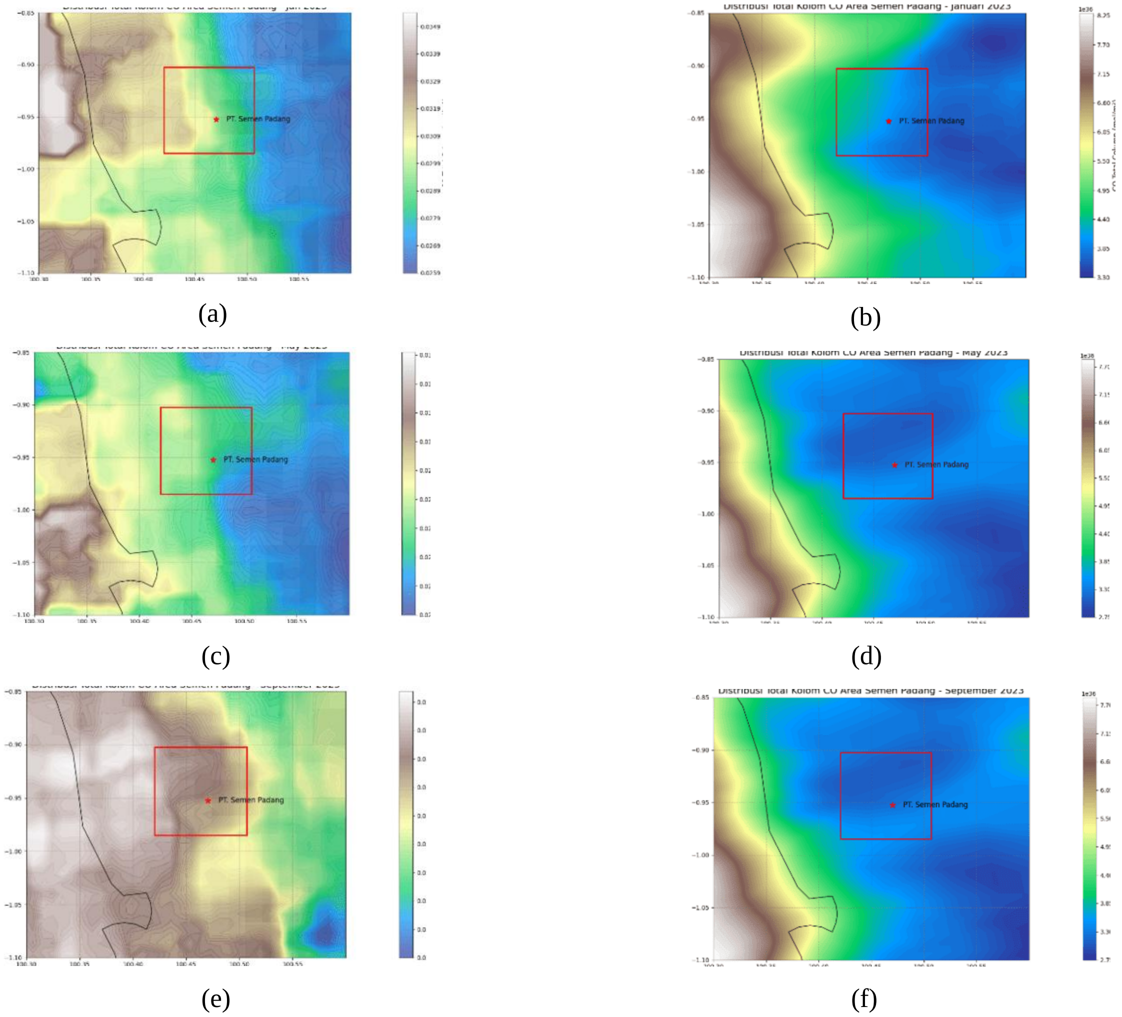


Figure 3 (a) The mean CO in January 2023 using Google Earth Engine (b) The mean CO in 2023 using Python Engine (c) The mean CO in May 2023 using Google Earth Engine (d) The mean CO in May 2023 using Python (e) The mean CO in September 2023 using Google Earth Engine (f) The mean CO in September 2023 using Python.

The spatial distribution of CO concentrations around PT. Semen Padang reveals significant temporal and spatial variations throughout 2023. From the visualization in Figure 3, there's a distinct pattern of CO accumulation that appears to be influenced by both industrial activities and local topography. The January 2023 measurements show elevated CO concentrations (approximately 0.04-0.05 mol/mm²) in the northeastern sector of the study area, particularly evident in both Google Earth Engine and Python-generated visualizations. This pattern suggests a possible influence of prevailing wind patterns during the winter monsoon period, which typically affects pollutant dispersion in this region.

The May 2023 data indicates a slight reduction in CO concentrations (ranging from 0.03-0.04 mol/mm²) compared to January, likely attributable to improved atmospheric mixing conditions during the transition season. The spatial distribution becomes more uniform across the study area, though hotspots remain visible around the industrial complex. The Python-generated analysis particularly highlights these patterns with better resolution, showing micro-scale variations that might be influenced by local terrain features and urban development.

September 2023 presents the most concerning CO distribution pattern, with concentrations reaching up to 0.06 mol/mm² in some areas. This increase could be attributed to reduced rainfall and stable atmospheric conditions typical of this period, which can limit pollutant dispersion. The comparative analysis between *Google Earth Engine* and *Python* processing methods reveals consistent patterns, validating the reliability of these observations. Of particular interest is the formation of CO pools in the valley areas, suggesting topographic influences on pollutant accumulation. This pattern is especially evident in the industrial zone's immediate vicinity, indicating a direct correlation between industrial activities and CO concentrations.

Sentinel-5P data showed carbon monoxide levels reaching peaks of 0.06 mol/mm² in September. This finding is consistent with the seasonal pattern reported by the Bukit Koto Tabang Global Atmosphere Watch (GAW) Station, which noted deteriorating air quality conditions in September compared to previous months (Nugroho, 2023). The GAW station's continuous monitoring provides essential validation for our satellite observations of elevated pollutant concentrations during this period.

3.2 Nitrogen dioxide (NO2)

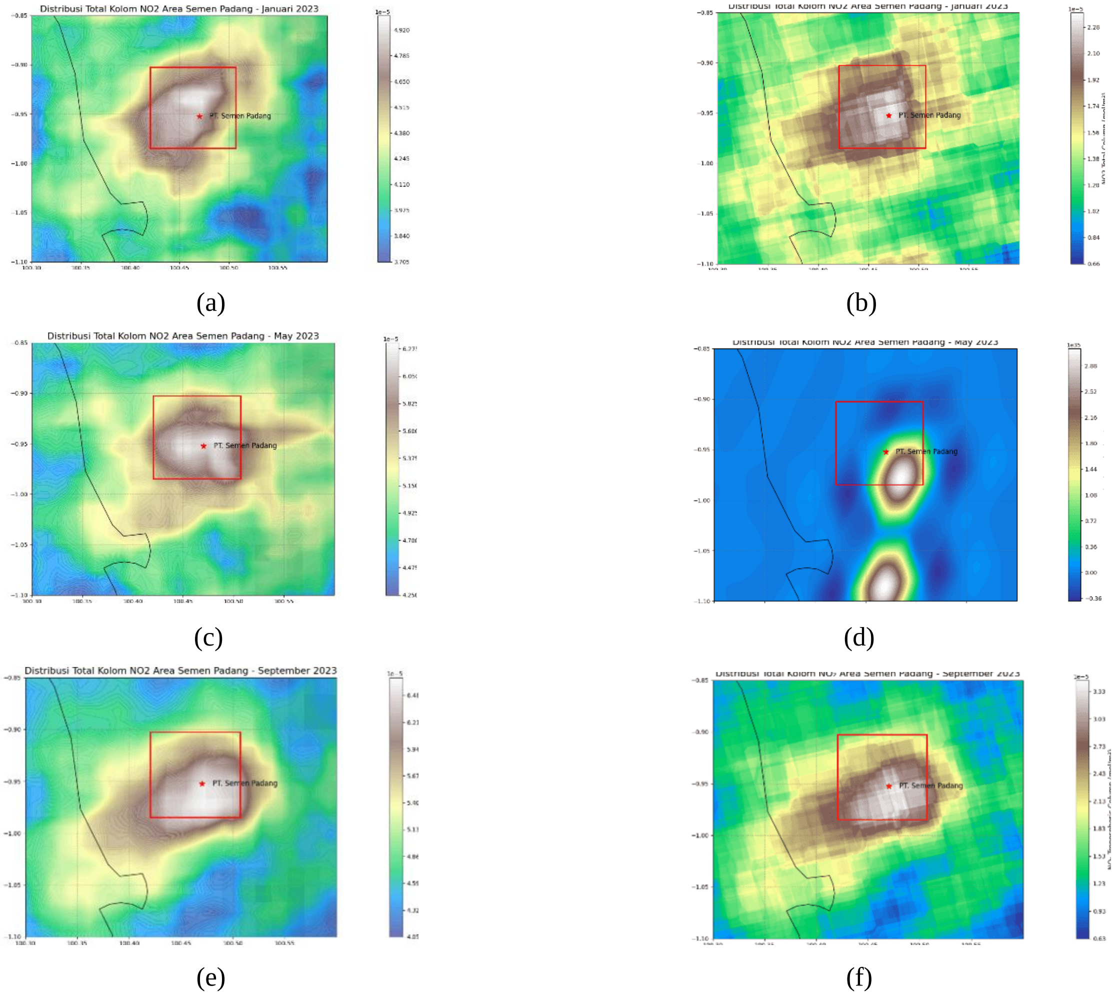


Figure 4 (a) The mean NO2 in January 2023 using *Google Earth Engine* (b) The mean NO2 in 2023 using *Python* (c) The mean NO2 in May 2023 using *Google Earth Engine* (d) The mean NO2 in May 2023 using *Python* (e) The mean NO2 in September 2023 using *Google Earth Engine* (f) The mean NO2 in September 2023 using *Python.*

The NO_2 distribution patterns illustrated in Figure 4 present a complex picture of pollution dynamics in the study area. January 2023 shows relatively high NO_2 concentrations (0.00015-0.00020 mol/mm²) concentrated around the industrial complex, with a clear gradient decreasing towards the peripheral areas. The spatial pattern suggests strong point source emissions, likely from both industrial processes and vehicular traffic in the urbanized sections of the study area. The high-resolution analysis from both platforms reveals interesting microscale variations that could be attributed to local emission sources and atmospheric chemistry processes.

May 2023 data indicated a moderate decrease in NO_2 levels (averaging 0.00012-0.00015 mol/mm²), possibly due to enhanced atmospheric mixing and increased precipitation during this period. The spatial distribution becomes more diffuse, though the industrial sector maintains relatively higher concentrations. An interesting feature observed in the Python-processed data is the presence of NO_2 plumes extending downwind from the main industrial area, suggesting active dispersion processes influenced by local meteorological conditions.

The September 2023 analysis shows the most intense NO_2 concentrations (reaching up to 0.00025 mol/mm²) with distinct hotspots around the cement facility. This period coincides with typically stable atmospheric conditions and reduced rainfall, leading to reduced pollutant dispersion. The comparison between processing methods reveals consistent spatial patterns, though the Python analysis provides finer detail in depicting concentration gradients. The observed pattern suggests a strong influence of industrial emissions combined with reduced atmospheric mixing, creating potential air quality concerns for nearby residential areas.

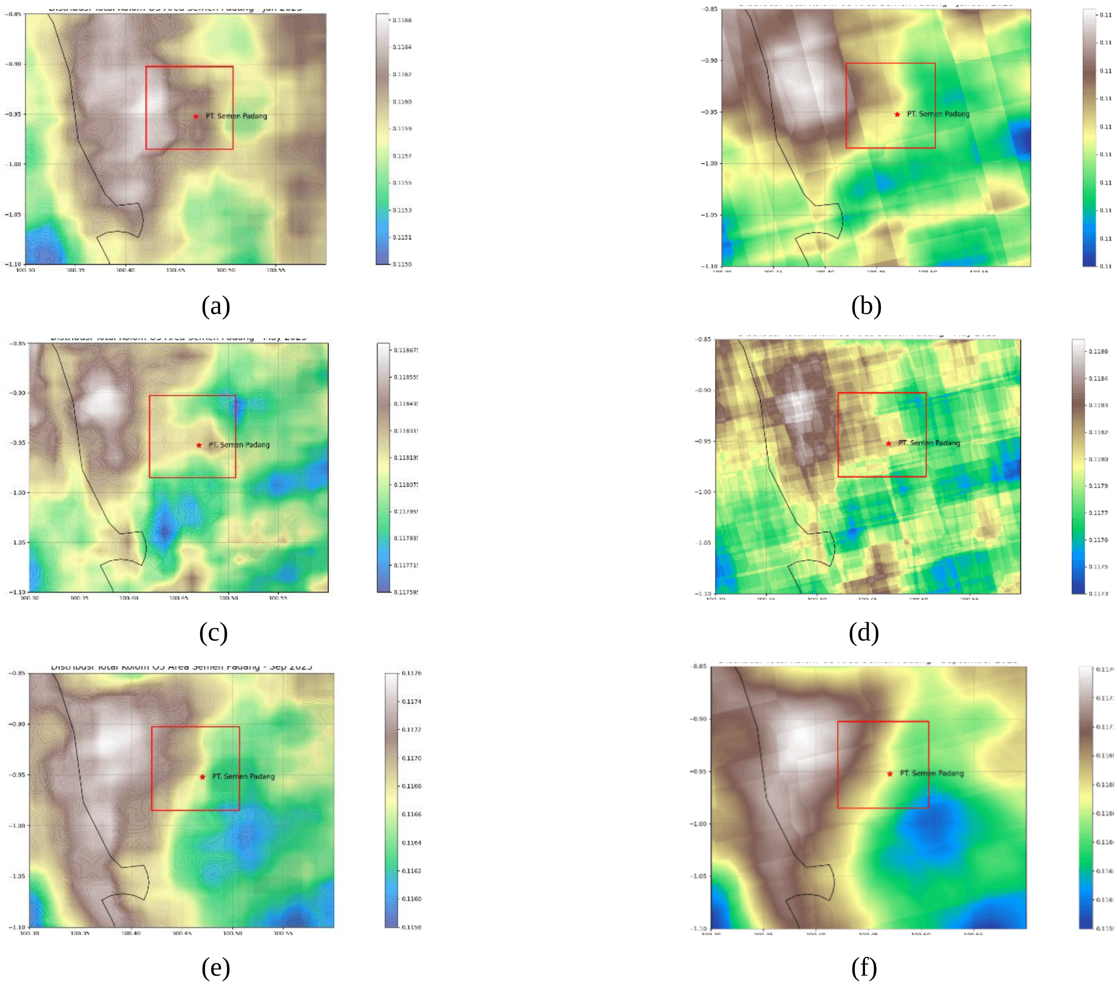


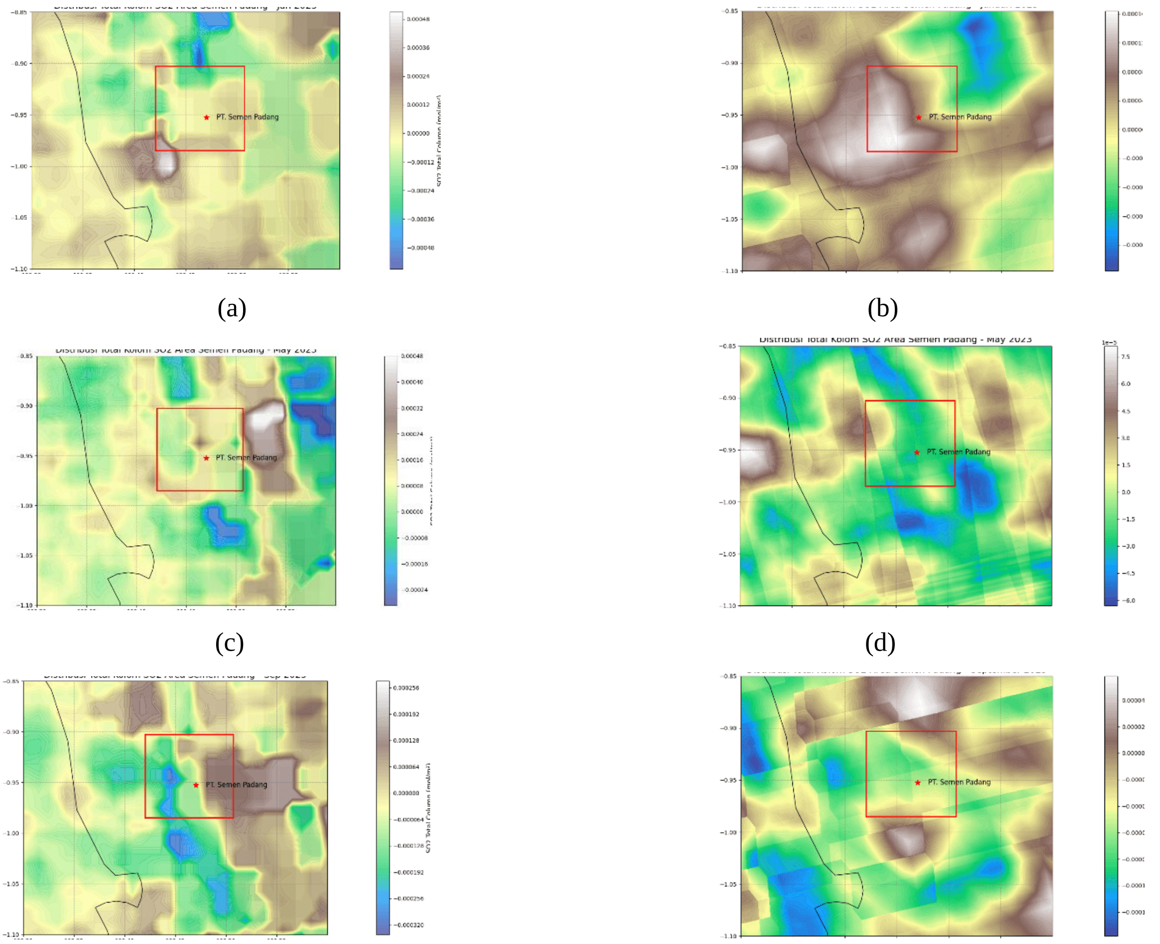
Figure 5 (a) The mean O3 in January 2023 using *Google Earth Engine* (b) The mean O3 in 2023 using *Python* (c) The mean O3 in May 2023 using *Google Earth Engine* (d) The mean O3 in May 2023 using *Python* (e) The mean O3 in September 2023 using *Google Earth Engine* (f) The mean O3 in September 2023 using *Python.*

NO_2 concentrations showed significant spatial variation with maximum values of 0.00025 mol/mm² near industrial sources. The spatial distribution closely follows the pattern of industrial activity, with highest concentrations observed downwind of PT. Semen Padang facilities. This pattern aligns with the documented weather patterns for the region during September, which typically features reduced wind speeds and more stable atmospheric conditions according to local meteorological station data.

3.3 Ozone (O3)

The O_3 distribution patterns shown in Figure 5 reveal interesting temporal and spatial variations that reflect both primary emissions and secondary atmospheric chemistry processes. January 2023 exhibits moderate O_3 concentrations (0.12-0.15 mol/mm²) with a relatively uniform distribution across the study area. This pattern suggests active photochemical processes despite the winter season, possibly influenced by high levels of precursor pollutants and adequate solar radiation even during this period.

The May 2023 analysis shows increased O_3 levels (0.15-0.18 mol/mm²) with distinct spatial variations. The Google Earth Engine and Python analyses both capture elevated concentrations in areas downwind of the industrial complex, indicating active photochemical production of O_3 from precursor pollutants. The spatial patterns suggest a complex interaction between industrial emissions, urban pollutants, and meteorological conditions affecting O_3 formation and transport.



(a) (b)
(c) (d)
(e) (f)

Figure 6 (a) The mean SO2 in January 2023 using *Google Earth Engine* (b) The mean SO2 in 2023 using *Python* (c) The mean SO2 in May 2023 using *Google Earth Engine* (d) The mean SO2 **i**n May 2023 using *Python* (e) The mean SO2 in September 2023 using *Google Earth Engine* (f) The mean SO2 in September 2023 using *Python.*

September 2023 presents the highest O_3 concentrations (reaching 0.20 mol/mm²) with clear spatial gradients extending from the industrial area. This period typically experiences higher temperatures and solar radiation, promoting photochemical O_3 production. The detailed spatial analysis reveals O_3 accumulation in suburban areas, suggesting transport and transformation of precursor pollutants. The comparative analysis between platforms shows consistent patterns, though the Python analysis provides better resolution of local variations.

The detection of elevated ozone concentrations (up to 0.20 mol/mm²) indicates active photochemical processes in the urban-industrial environment. These elevated levels coincide with the period of increased solar radiation typically experienced in the region during September, as recorded by local meteorological stations. The formation of secondary pollutants like ozone is particularly concerning given the already compromised air quality reported by ground monitoring stations during this period.

3.4 Sulfur Dioxide

The SO_2 distribution patterns depicted in Figure 6 show significant spatial and temporal variations throughout the study period. January 2023 exhibits moderate SO_2 concentrations (0.0004-0.0005 mol/mm²) with clear hotspots around the industrial complex. The spatial pattern suggests direct emissions from industrial processes, with concentration gradients indicating dispersion patterns influenced by local meteorology and topography. May 2023 shows slightly reduced SO_2 levels (0.0003-0.0004 mol/mm²) with a more diffuse spatial distribution. Both processing methods capture similar patterns, though the Python analysis reveals finer-scale variations in concentration gradients. The observed distribution suggests improved dispersion conditions during this period, though industrial emissions remain evident in the spatial patterns. The September 2023 analysis presents elevated SO_2 concentrations (up to 0.0006 mol/mm²) with distinct spatial patterns indicating strong source influences. The high-resolution analysis reveals clear plume patterns extending from the industrial area, suggesting active emission sources and limited dispersion under stable atmospheric conditions. The comparative analysis between platforms provides consistent results, validating the observed patterns and their interpretation in terms of source-receptor relationships in the study area. Sulfur dioxide patterns, with concentrations up to 0.0006 mol/mm², clearly demonstrate the influence of industrial emissions on local air quality. The spatial correlation between SO_2 concentrations and industrial facilities is particularly evident in our analysis. This finding is substantiated by the deteriorating air quality metrics reported by local environmental authorities during the same period.

4. CONCLUSION

This study provides concrete evidence of seasonal air quality variations near PT. Semen Padang, with September 2023 showing the highest pollutant concentrations as verified by both satellite data and ground measurements (AQI 102 on September 13; PM2.5 at 61 μg/m³ on September 3). The integration of Sentinel-5P observations with data from local AQMS and GAW stations confirms deteriorating air quality from August through September 2023, as corroborated by environmental authorities (Mairizon, 2023; Nugroho, 2023).

Our analysis documents concerning pollution levels: CO (0.06 mol/mm²), NO_2 (0.00025 mol/mm²), O_3 (0.20 mol/mm²), and SO_2 (0.0006 mol/mm²). The spatial distribution of these pollutants shows clear correlation with industrial activities and is exacerbated during periods of reduced rainfall and lower wind speeds in Padang Municipality (0°44'-01°08' S, 100°05'-100°34' E).

The documented classification of air quality as "unhealthy for sensitive groups" during September highlights the urgent need for enhanced emission controls during unfavorable meteorological conditions. Future research should establish integrated monitoring networks combining satellite and expanded ground-based measurements to better understand air quality dynamics in this rapidly developing industrial region.

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