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Artikel Penelitian

Long-Term Passive Sampler Monitoring of NO_2 and SO_2 for Trend Analysis and Control Strategies in South Sumatra

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ABSTRACT

Air pollution is one of the most pressing environmental issues, with direct impacts on human health and overall environmental quality. The increasing intensity of transportation activities, industrial operations, forest and land fires, and regional development in South Sumatra Province has led to a growing risk of air pollution, particularly from Nitrogen Dioxide (NO_2) and Sulfur Dioxide (SO_2). This study aims to analyze the concentrations and multi-year trends of NO_2 and SO_2 in South Sumatra based on Passive Sampler measurements conducted at 68 monitoring sites across 17 districts and municipalities from 2021 to 2024. The results indicate that the average concentrations of NO_2 ranged from 6.654 to 9.944 µg/m³ while SO_2 ranged from 7.303 to 8.456 µg/m³, both of which remain below the National Ambient Air Quality Standards and the European Union guideline values. The multi-year trend analysis shows a consistent decline in concentrations from 2021 to 2024. These findings provide an important contribution to long-term air quality data availability and knowledge of NO_2 and SO_2 dynamics, serving as a scientific foundation for formulating evidence-based strategies for air pollution control and prevention in the region.

Keyword: NO_2, Passive Sampler, SO_2, South Sumatra, Pollution Trends.

ABSTRAK

Pencemaran udara merupakan salah satu isu lingkungan yang paling mendesak karena berdampak langsung pada kesehatan manusia dan kualitas lingkungan secara keseluruhan. Meningkatnya intensitas aktivitas transportasi, operasi industri, kebakaran hutan dan lahan, serta perkembangan wilayah di Provinsi Sumatera Selatan telah meningkatkan risiko terjadinya pencemaran udara, khususnya yang berasal dari Nitrogen Dioksida (NO_2) dan Sulfur Dioksida (SO_2). Penelitian ini bertujuan untuk menganalisis konsentrasi dan tren tahunan NO_2 dan SO_2 di Sumatera Selatan berdasarkan pengukuran Passive Sampler yang dilakukan pada 68 lokasi pemantauan di 17 kabupaten dan kota dari tahun 2021 hingga 2024. Hasil penelitian menunjukkan bahwa rata-rata konsentrasi NO_2 berkisar antara 6,654 hingga 9,944 µg/m³, sedangkan SO_2 berkisar antara 7,303 hingga 8,456 µg/m³. Kedua rentang nilai tersebut masih berada di bawah Baku Mutu Udara Ambien Nasional maupun nilai panduan Uni Eropa. Analisis tren multi-tahun menunjukkan penurunan konsentrasi yang konsisten dari tahun 2021 hingga 2024. Temuan ini memberikan kontribusi penting terhadap ketersediaan data kualitas udara jangka panjang dan pemahaman mengenai dinamika NO_2 dan SO_2, serta menjadi dasar ilmiah dalam merumuskan strategi pengendalian dan pencegahan pencemaran udara berbasis bukti di wilayah tersebut.

Kata Kunci: NO_2, Sampler Pasif, SO_2, Sumatra Selatan, Tren Polusi.

1. INTRODUCTION

Air pollution remains one of the most critical global environmental and public health issues, ranking as the second leading risk factor for mortality among vulnerable populations such as children and the elderly. The State of Global Air (2021) estimated that ambient air pollution contributed to approximately 8.1 million deaths worldwide, with lower- and middle-income countries disproportionately affected due to their reliance on fossil fuels, biomass combustion, and industrial activities (Ritchie & Rosado, 2025). In Central Asia, South Asia, and Southeast Asia,

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air pollution accounted for more than 3.4 million deaths in 2021. In Indonesia, elevated exposure to nitrogen dioxide (NO_2) and sulfur dioxide (SO_2) has been linked to increased risk of acute respiratory infections, particularly among children aged 0–3 years (Suryadhi et al., 2020).

NO_2 and SO_2 originate from various anthropogenic sources, resulting in complex spatial and temporal distribution patterns. Fossil fuel combustion remains the dominant contributor globally, although regional variations exist. In urban environments, vehicular emissions constitute the primary source of NO_2 (Dandotiya, Jadon, & Sharma, 2019; Meng et al., 2008), while SO_2 emissions are largely associated with industrial processes and domestic fuel use (Meng et al., 2008). Concentrations of both pollutants tend to be higher in commercial and high-traffic zones compared to residential areas, indicating strong local influence from human activities (Dandotiya et al., 2019; Sharma & Raina, 2012). In urban environments, vehicular emissions constitute the primary source of NO_2 (Dandotiya, Jadon, & Sharma, 2019; Meng et al., 2008), a pattern also observed in Indonesian cities where transportation contributed more than 90% of total NO_2 emissions in northern Semarang (Hadiwidodo & Huboyo, 2006).

The need for accurate monitoring and effective emission control strategies is therefore critical. Technologies such as flue gas desulfurization (FGD) have been widely adopted to mitigate SO_2 emissions, while post-combustion control systems are commonly implemented to reduce NO_2 formation at the source (Arghya Sardar, 2015; Sun, Zwolińska, & Chmielewski, 2016). Atmospheric dispersion models and ambient air monitoring networks also support the evaluation of emission reduction strategies (Ozkurt et al., 2013).

However, conventional monitoring networks remain limited due to high installation and maintenance costs and uneven spatial distribution, particularly in resource-constrained regions (Byanju, Gewali, & Manandhar, 2012). This lack of dense observation networks can hinder accurate representation of spatial pollution gradients and impede comprehensive exposure assessments (Huang et al., 2024). Dimitropoulou et al. (2020) further emphasized that high-resolution observations are essential for capturing near-surface NO_2 variability in areas with heterogeneous emission sources. Consequently, alternative approaches that enable wider spatial coverage, such as passive samplers, play an important complementary role in regional air quality assessment.

Passive samplers offer an effective, low-cost alternative suitable for widespread deployment in remote or under-resourced regions. Operating via molecular diffusion into a chemically treated sorbent, they require no external power and are simple to operate. Their reliability has been validated by the World Meteorological Organization (WMO, 2003). Studies have demonstrated strong agreement between passive and active monitoring methods: Plaisance et al. (2002) reported detection limits of 2.3 $\mu g/m^3$ for NO_2 and 4.2 $\mu g/m^3$ for SO_2 with correlation coefficients exceeding 0.8, while He et al. (2014) found similar performance in tropical Singapore.

Despite these advantages, long-term passive sampling studies remain limited in Indonesia. Existing research tends to focus on short-term monitoring or limited spatial coverage, leaving significant gaps in understanding long-term pollutant dynamics. Leveraging multi-year passive sampler data is crucial for identifying temporal trends, evaluating spatial variability, and supporting evidence-based air pollution control strategies. Expanding such approaches, particularly in regions like South Sumatra with diverse anthropogenic and environmental influences, can substantially improve air quality management and public health outcomes.

2. METHODOLOGY

This study focused on analyzing the trends in ambient air quality in South Sumatra Province for Nitrogen Dioxide (NO_2) and Sulfur Dioxide (SO_2) over four years (2021–2024) based on field monitoring data. The analysis was carried out by examining pollutant concentrations obtained from Passive Sampler measurements using statistical linear regression methods. The selection of sampling locations across the 17 districts and municipalities in South Sumatra Province was based on the objective of capturing representative long-term trends of NO_2 and SO_2 concentrations at the provincial scale using passive sampler monitoring data from 2021 to 2024. All administrative areas were included to ensure spatial representativeness and consistency in trend analysis, in accordance with the Environmental Quality Index framework stipulated in Regulation of the Ministry of Environment and Forestry of the Republic of Indonesia No. 27 of 2021. Wind rose analysis was not incorporated in this study because the passive sampler method provides time-averaged concentrations over a 14-day exposure period and is not intended to capture short-term variations associated with wind direction and wind speed. Therefore, the methodology focused on temporal and spatial trends of pollutant concentrations, while wind-related dispersion analysis is recommended for future studies using continuous meteorological data. The Passive Sampler deployment sites are presented in Figure 1.

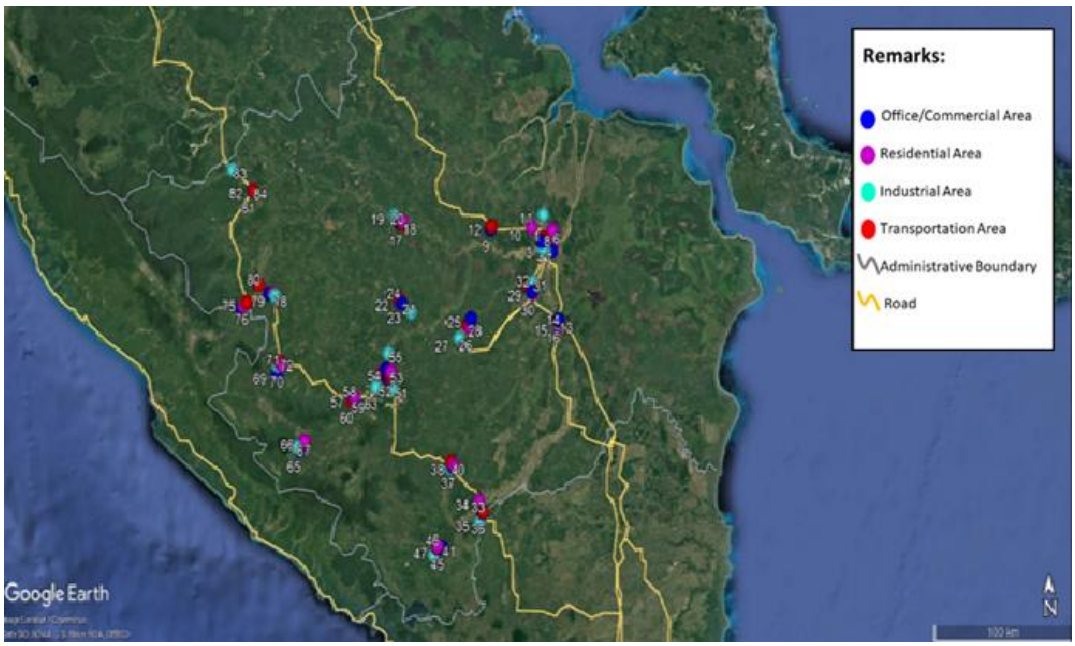


Figure 1. Locations of Passive Sampler Deployment in South Sumatra Province

The ambient air quality data used in this study were collected from 68 monitoring sites distributed across 17 districts/municipalities in South Sumatra Province from 2021 to 2024. Each district/municipality contained four monitoring sites, determined based on the Regulation of the Ministry of Environment and Forestry No. 27 of 2021 on the Environmental Quality Index. The criteria for monitoring locations included: high-traffic or transportation areas, industrial zones, densely populated residential areas, and office zones not directly influenced by transportation. Ambient air sampling was conducted over a period of 14 days, with a frequency of two times per year, representing both the dry and wet seasons, using the *Passive Sampler* method (see **Figure 2**).

Figure 2. Passive Sampler
Source: Cruz et al., 2004

The concentration and trend data for NO_2 and SO_2 from multi-year *Passive Sampler* monitoring were compiled using Microsoft Excel, where each dataset represented the average measurement over the 14-day sampling period. Before conducting trend analysis, annual and multi-year data processing was performed. Annual data analysis, including boxplot visualization, was carried out using Python, while multi-year data processing was conducted in Excel. Finally, linear regression analysis using Microsoft Excel was applied to assess the trends in NO_2 and SO_2 concentrations obtained from *Passive Sampler* monitoring.

3. RESULT AND DISCUSSION

3.1. General Description of NO_2 and SO_2 Concentrations

The concentrations of NO_2 and SO_2 in the atmosphere were measured twice a year. The first monitoring period was conducted between April and June, while the second period was carried out between July and November, representing seasonal variations. Measurements were taken at four monitoring sites in each district/municipality,

covering representative locations of office or commercial areas, residential zones, industrial areas, and transportation corridors.

The results of NO_2 and SO_2 concentration measurements during the 2021–2024 period in South Sumatra Province revealed clear spatial and seasonal variations, with concentrations generally higher during the dry season. This seasonal pattern is consistent with satellite-based observations reported in remote sensing studies, which indicate elevated NO_2 and SO_2 concentrations during dry seasons due to limited wet deposition and intensified anthropogenic activities (Lin et al., 2019; Zhou et al., 2019). These findings highlight the crucial role of meteorological factors, particularly rainfall, in regulating ambient air pollutant levels in South Sumatra.

In addition to meteorological conditions, anthropogenic activities also serve as key determinants of air quality. In South Sumatra, increases in pollutant concentrations were generally associated with transportation, industrial activities, and particularly forest and land fires that frequently occur during the dry season. This observation aligns with the findings of Lukman et al. (2025), who emphasized that transportation, industry, and biomass burning are the dominant sources of NO_2 and SO_2 emissions in Indonesia.

From a public health perspective, although the concentrations of NO_2 and SO_2 observed at several monitoring sites remained below the national ambient air quality standards, potential health risks should not be overlooked. Widodo and Arifin (2024) demonstrated that long-term exposure to air pollutants, including NO_2 and SO_2, is significantly associated with increased cases of asthma and chronic obstructive pulmonary disease (COPD) in urban populations in Indonesia. This suggests that even relatively low pollutant concentrations can pose serious health risks to vulnerable groups such as children and the elderly.

Overall, the general description of NO_2 and SO_2 concentrations in South Sumatra indicates seasonal and spatial patterns that are consistent with both global and regional literature. These findings strengthen the understanding that meteorological conditions, anthropogenic activities, and biomass burning are key factors influencing air quality, with implications extending beyond environmental degradation to public health concerns.

3.2. NO_2 Concentration in South Sumatra Province Based on Passive Sampler Data in 2021

The monitoring results using passive samplers in 2021 showed that NO_2 concentrations across 17 districts and municipalities in South Sumatra Province ranged from 6.65 to 9.94 μg/m³. These values remain well below the European Union (EU) guideline value of 40 μg/m³. Figure 2 illustrates the variation and fluctuation of NO_2 concentrations across different periods and administrative regions of South Sumatra Province in 2021.

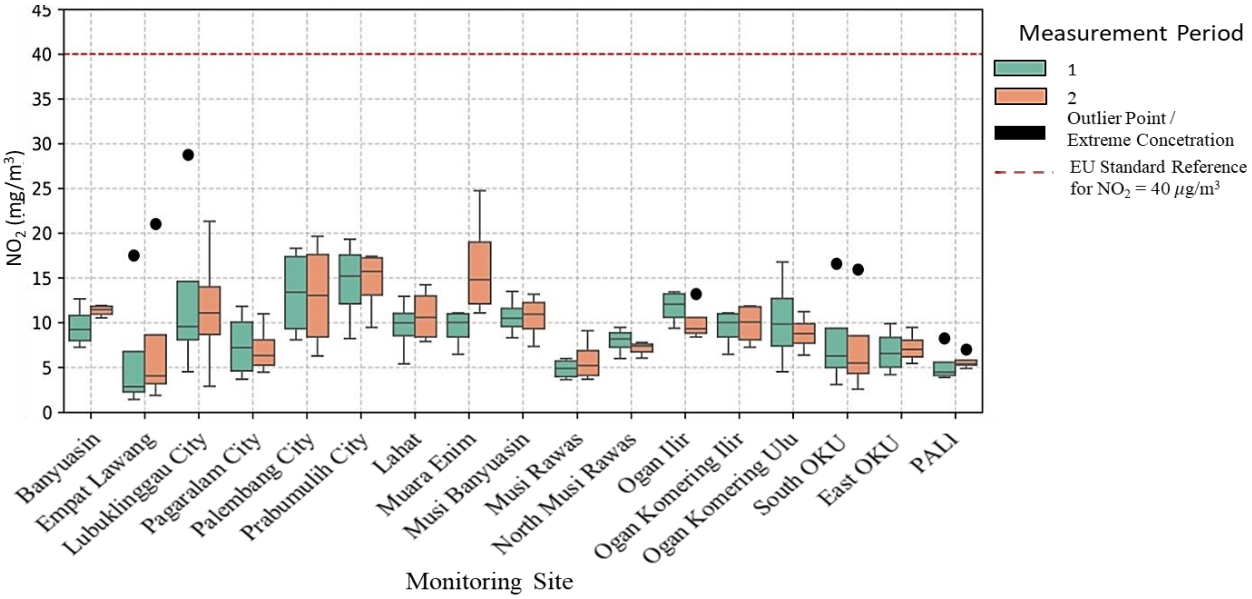


Figure 3. NO_2 Concentration in South Sumatra Province Based on Passive Sampler Data in 2021

As illustrated in Figure 2, the median values, box heights between periods, and whisker ranges indicate that the fluctuations in NO_2 concentrations were not highly significant. Several regions, namely Empat Lawang District, Lubuklinggau City, Palembang City, Lahat District, Muara Enim District, Musi Rawas District, and Ogan Komering Ilir (OKI) District, experienced an increase in concentrations during the second period, while other locations showed either a decrease or remained relatively stable. The increase observed in the second period was largely attributed to the gradual recovery of activities across various sectors in early 2021 following the COVID-19 pandemic, particularly from the transport sector. However, since many offices continued implementing work-from-home (WFH) arrangements for employees, the fluctuations and increases in NO_2 levels were relatively minor.

These observations are consistent with global studies highlighting the strong influence of human mobility on NO_2 concentrations. Satellite-based analyses by Bauwens et al. (2020) reported pronounced decreases in tropospheric NO_2 columns during periods of restricted activity across multiple regions worldwide. The agreement between these global findings and the relatively limited NO_2 fluctuations observed in this study suggests that changes in anthropogenic activity, particularly mobility-related emissions, remain a key driver of NO_2 variability, even beyond the acute lockdown phase.

This phenomenon is consistent with the findings of Ariati et al. (2024) in Makassar, which demonstrated that traffic volume directly influences NOx concentrations (including NO_2), confirming that road transport is one of the primary contributors to urban air pollution. These results are further supported by Syahputri et al. (2023), who emphasized that the transportation sector accounts for a substantial proportion of urban air pollution in Indonesia. Their study highlighted that exposure to transport-related pollutants, particularly NO_2, poses serious public health risks and necessitates control strategies grounded in the Avoid–Shift–Improve (ASI) framework, reducing travel demand, shifting towards public or environmentally friendly modes of transport, and improving vehicle efficiency.

3.3. NO_2 Concentration in South Sumatra Province Based on Passive Sampler Data in 2022

The passive sampler measurements in 2022 indicated that the median NO_2 concentration during the first period ranged between 2.39 and 12.95 µg/m³, while in the second period it increased to 4.18–14.07 µg/m³. Overall, the NO_2 concentrations in 2022 showed a decline compared to 2021. This reduction was closely associated with the decrease in forest and land fires, which have long been recognized as one of the major contributors to air pollution in South Sumatra Province. Nevertheless, Figure 3 illustrates notable variations across districts and municipalities, with several areas such as Banyuasin, Empat Lawang, Palembang, Muara Enim, Musi Banyuasin, Musi Rawas, Musi Rawas Utara, East OKU, and PALI recording higher concentrations during the second period. This increase is likely linked to the gradual recovery of community activities, transportation, and industrial operations following the COVID-19 pandemic.

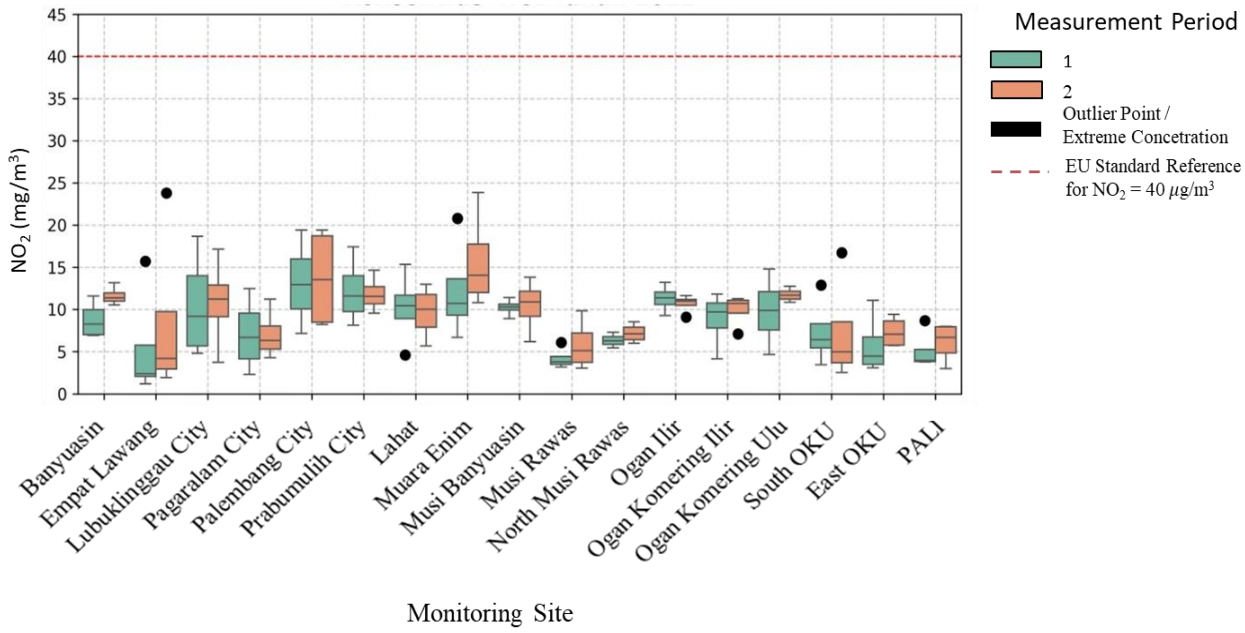


Figure 4. NO_2 Concentrations in South Sumatra Province Based on Passive Sampler Measurements in 2022

As shown in Figure 4, while the overall NO_2 concentrations decreased from 2021, localized increases in certain regions reflected differences in emission sources and local conditions. For instance, the decline in fire incidents contributed to reduced pollution in some districts, whereas others experienced increases due to urbanization, traffic intensity, and industrial emissions. These patterns are consistent with recent findings in Indonesia, where the transport and industrial sectors have been identified as dominant contributors to urban air pollution.

Recent advances in satellite-based NO_2 retrievals have further strengthened the interpretation of spatial and temporal variability of nitrogen dioxide concentrations. Improvements in the TROPOMI NO_2 retrieval algorithm have significantly reduced the underestimation of tropospheric NO_2, particularly over polluted and urbanized regions, enabling more reliable assessment of emission patterns related to transport and industrial activities (Geffen et al., 2022). In line with this, previous studies have emphasized the strong correlation between traffic density and NOx levels in urban environments.

Moreover, the strong spatial variability observed across districts is consistent with studies showing that urban NO_2 concentrations are highly heterogeneous and strongly influenced by local emission sources. Judd et al. (2020)

emphasized that such spatial heterogeneity must be carefully considered when interpreting NO_2 measurements, particularly when integrating ground-based observations with satellite-based products.

3.4. NO_2 Concentration in South Sumatra Province Based on Passive Sampler Data in 2023

In 2023, nitrogen dioxide (NO_2) concentrations in South Sumatra Province showed a notable increase compared to the previous year, even reaching the highest peak observed during the entire monitoring period. Measurements obtained using passive samplers indicated that, in the first period, the median concentration of NO_2 ranged from 3.64 to 15.93 µg/m³, while in the second period the values slightly declined within the range of 6.23 to 15.49 µg/m³. Figure 4 illustrates these variations across districts and municipalities, revealing that the upward trend in concentrations was more evenly distributed compared to previous years.

This increase was strongly associated with the extensive forest and land fires (karhutla) that, in 2023, recorded the largest burned area among all years of observation. These intensive fires not only released direct emissions of NO_2 and other pollutants but also worsened air quality through the rise of particulate matter and subsequent atmospheric chemical reactions. Zhang et al. (2022) emphasized that biomass burning in Southeast Asia substantially contributes to the release of pollutants such as NOx, CO, and particulates, which elevate atmospheric concentrations and further stimulate the formation of ozone and other secondary pollutants via photochemical reactions.

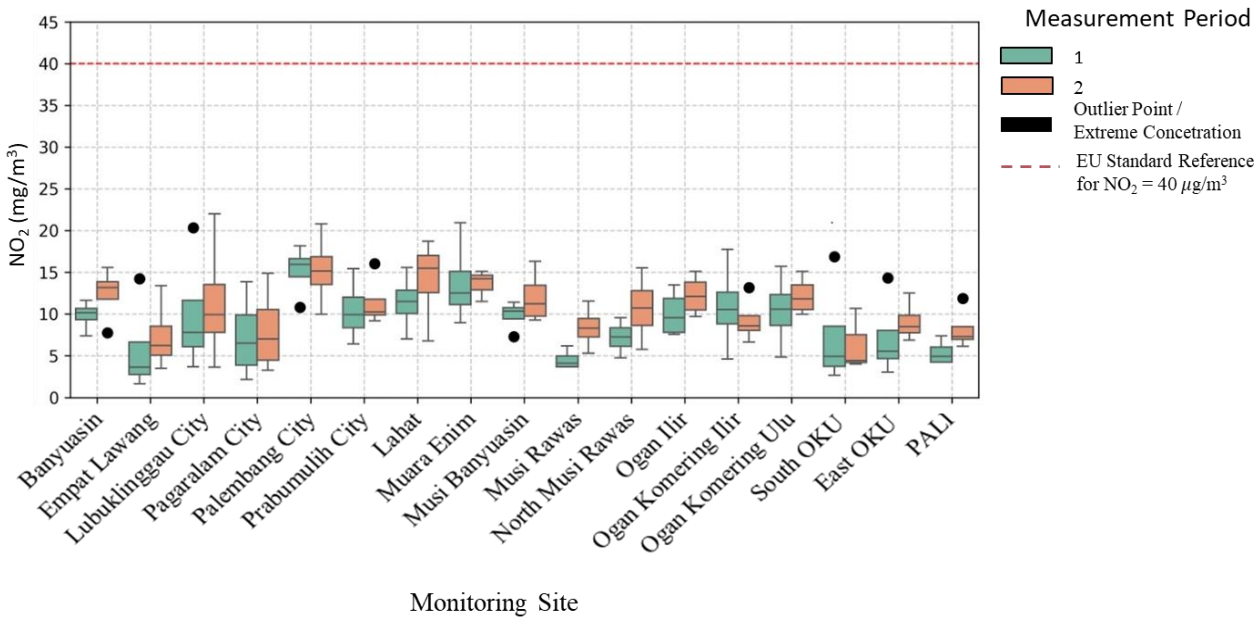


Figure 5. NO_2 Concentrations in South Sumatra Province Based on Passive Sampler Measurements in 2023

As shown in Figure 5, most locations experienced an increase during the second period, with twelve sites recording higher concentrations: Banyuasin, Empat Lawang, Lubuklinggau City, Pagaralam City, Palembang City, Lahat, Musi Banyuasin, Musi Rawas, North Musi Rawas, Ogan Ilir, East OKU, and PALI. This pattern suggests that both anthropogenic and natural factors worked simultaneously to worsen air quality. In addition to the impact of forest and land fires, the increase was also associated with the resurgence of activities across multiple sectors, including industry, transportation, and offices, as well as the commencement of development projects that had been delayed during the pandemic. Conversely, some regions showed relatively stable or slightly decreased concentrations, most likely influenced by local meteorological conditions such as rainfall and wind direction that supported pollutant dispersion. Overall, the 2023 results underscore the importance of air quality management strategies that address not only forest and land fire mitigation but also the regulation of urban and industrial emissions, given their significant contribution to the rise of NO_2 concentrations in South Sumatra Province.

3.5. NO_2 Concentration in South Sumatra Province Based on Passive Sampler Data in 2024

When examined longitudinally from 2021 to 2024, NO_2 concentrations in South Sumatra Province exhibited a fluctuating pattern with clear spatial and temporal variations (Table 1). During the early period (2021–2022), concentrations remained relatively high, with several significant outliers particularly observed in transportation and industrial areas. This condition reflects the strong contribution of post-pandemic economic activities that had resumed at increasing intensity. Entering 2023, although the median values were not substantially different from the previous year, concentration spikes were still evident at several locations, especially in industrial and transportation zones, underscoring that these sectors continued to be the dominant sources of NO_2 emissions.

In 2024, however, a more pronounced decline was observed in both periods, marking the lowest concentrations throughout the four years of monitoring. Figure 5 illustrates that the distribution of concentration data across locations was relatively more uniform, with shorter whiskers and lower medians compared to previous years. This phenomenon may be attributed to improvements in meteorological conditions, such as more consistent rainfall, as well as potential pollution control efforts in the industrial and transportation sectors. The decline also suggests that environmental factors may play a more dominant role in determining NO_2 concentrations than variations in emissions alone. This interpretation is supported by recent satellite-based studies showing that interannual variability in NO_2 concentrations can be strongly driven by meteorological conditions, and that emission changes alone may not fully explain observed trends (Lange et al., 2022).

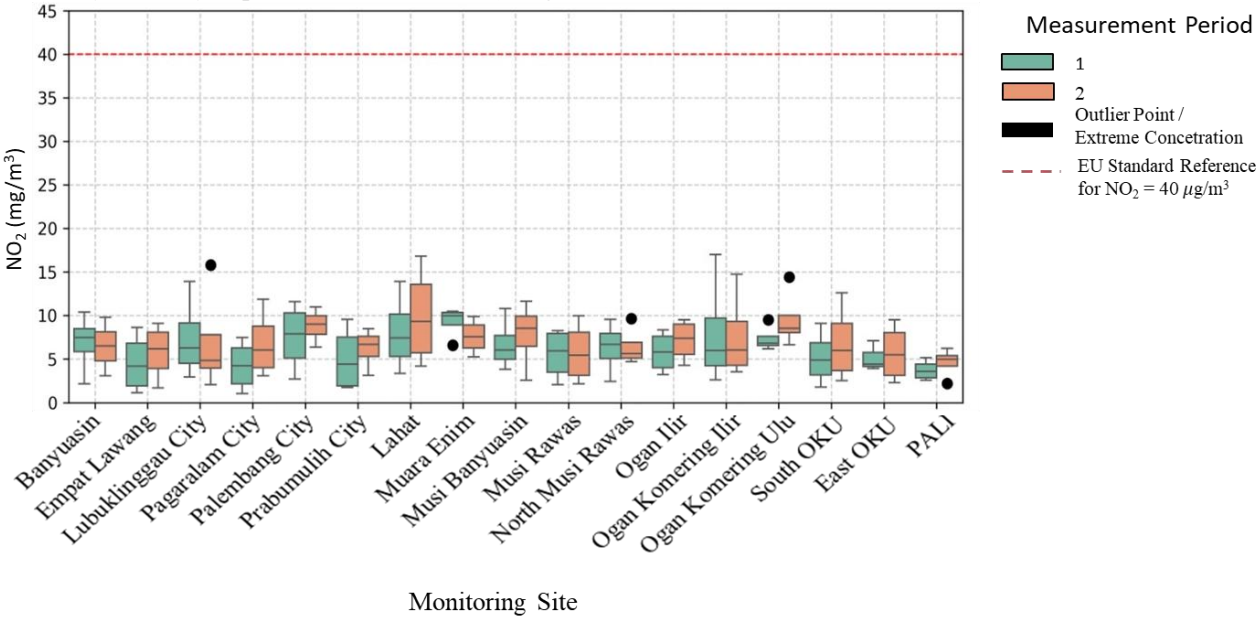


Figure 6. NO_2 Concentrations in South Sumatra Province Based on Passive Sampler Measurements in 2024

Table 1. Summary of Average NO_2 Concentrations in South Sumatra Province, 2021–2024

Year & Period	Average Concentration (µg/m³)	Outliers (Extreme Spikes)	Remarks
2021			
Period 1	4,84 - 14,48	4 upper outliers from transportation sources	Within the ambient air quality standard
Period 2	5,31 - 16,34	4 upper outliers from transportation and office areas	Within the ambient air quality standard
2022			
Period 1	4,19 - 13,12	5 upper outliers from transportation and industry; 1 lower outlier from the residential area	Within the ambient air quality standard
Period 2	5,78 - 15,70	2 upper outliers from transportation; 2 lower outliers from office areas	Within the ambient air quality standard
2023			
Period 1	4,51 - 15,20	4 upper outliers from transportation; 2 lower outliers from residential areas	Within the ambient air quality standard
Period 2	6,36 - 15,28	3 upper outliers from industry and transportation; 1 lower outlier from office areas	Within the ambient air quality standard
2024			
Period 1	3,71 - 9,27	1 upper outlier from the industry; 1 lower outlier from the residential area	Within the ambient air quality standard
Period 2	4,59 - 9,92	3 upper outliers from the industry; 1 lower outlier from the residential area	Within the ambient air quality standard

The recapitulation of NO_2 concentrations is presented in Table 1. As shown, NO_2 concentrations in South Sumatra Province, based on passive sampler monitoring, generally increased during the second monitoring period. Period two was conducted between July and September, when rainfall levels were relatively lower compared to period one, thereby influencing the measured NO_2 concentrations. Rainfall provides a natural "*washing*" effect on pollutants, as raindrops capture gaseous pollutants from the atmosphere and transport them to the ground. Daily rainfall has been reported to influence NOx concentrations, albeit weakly, with a negative correlation of r = –0.17 (Wantari and Turyanti, 2024). The negative correlation indicates that when rainfall is low, NOx concentrations tend to increase, and conversely, higher rainfall reduces pollutant accumulation. Low rainfall therefore reduces the effectiveness of natural mechanisms to remove atmospheric pollutants, including NO_2, allowing pollutants to persist longer in the air. Consequently, although the 2024 NO_2 concentrations remain below the national ambient air quality standard of 40 µg/m³, seasonal variations and meteorological factors should be carefully considered in developing effective air quality management strategies in South Sumatra Province.

3.6. Trends of NO_2 Concentration Using Passive Sampler in South Sumatra Province 2021–2024

In general, the annual NO_2 concentration trends in South Sumatra Province during 2021–2024 exhibited a fluctuating pattern, characterized by increases in the second monitoring period of each year, followed by a notable decline in 2024 across nearly all regions (Figure 6). This pattern highlights the influence of seasonal factors, particularly the reduced rainfall during July–September, which promotes the accumulation of pollutants (Wantari & Turyanti, 2024). Recorded concentrations remained below 30 µg/m³, indicating that overall air quality is still within the safe category according to the EU threshold (40 µg/m³ for passive sampler data). The reliability of passive sampler measurements has been widely demonstrated through inter-comparison studies showing good agreement with active reference methods, particularly in tropical urban environments (He et al., 2014). Nevertheless, the observed seasonal fluctuations remain an important issue to address, as they may have adverse health implications, particularly for vulnerable populations in densely populated urban areas.

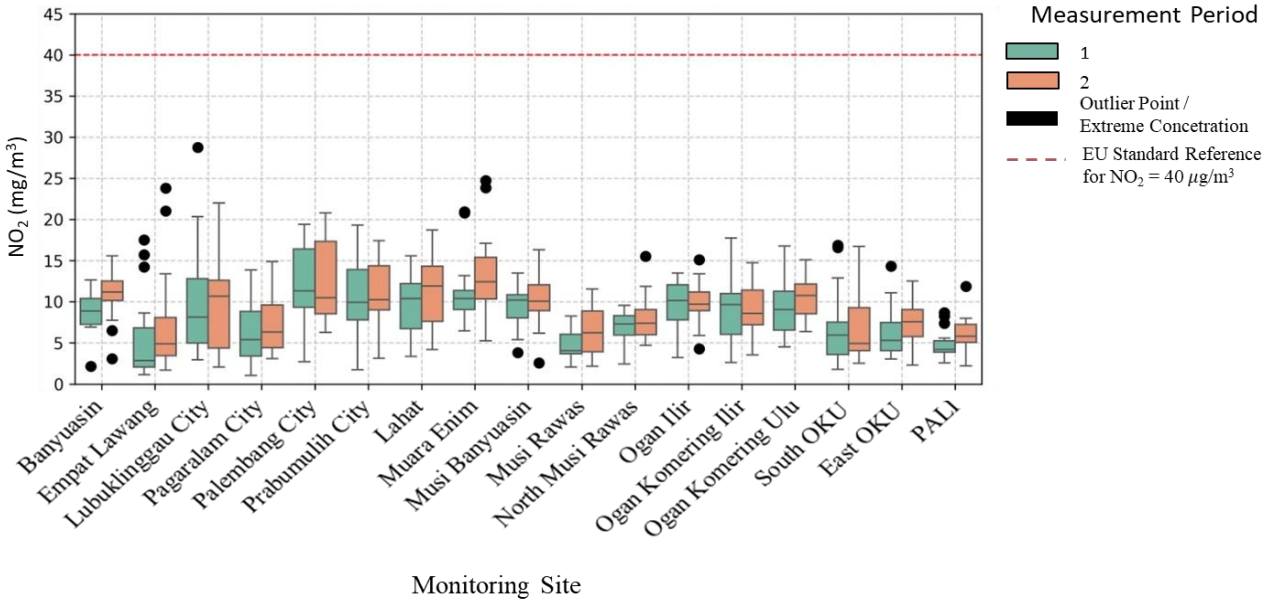


Figure 7. Trends in Inter-Period NO_2 Concentrations in South Sumatra Province Based on Passive Sampler Data 2021 to 2024

The multi-year trend of NO_2 concentrations during the 2021–2024 period, based on average values measured by passive samplers and analyzed using linear regression, is presented in Figure 7 and Table 2.

A more detailed analysis of Figure 7 and Table 2 highlights interesting spatial variations. Several districts, such as Lahat, Musi Rawas, and Musi Rawas Utara, exhibited increases in NO_2 concentrations during certain periods, although the overall annual trend shows a gradual decline. Palembang City, as the economic and transportation hub of the province, experienced a significant rise in concentrations until 2023, followed by a sharp decline in 2024. Conversely, areas such as Lubuklinggau, Prabumulih, and South Ogan Komering Ulu (OKU Selatan) consistently showed decreasing trends throughout the monitoring period. These differences reflect the strong linkage between local activity characteristics, such as transportation intensity, industrial presence, and population density, and pollutant concentration patterns. The decline observed in 2024 may also be attributed to more favorable meteorological conditions, as well as structural behavioral shifts in society driven by digitalization and the expansion of remote working practices that have reduced daily mobility (Lee, 2023).

Barré et al. (2021) reported a substantial decrease in NO_2 concentrations across Europe during COVID-19 lockdown periods, particularly in densely populated and transportation-dominated areas. Importantly, their study highlighted that accurate interpretation of multi-year trends requires accounting for meteorological influences to avoid overestimating the effect of emission reductions. In this study, the declining NO_2 trend observed in 2024 likely reflects a combined influence of reduced anthropogenic activities, structural changes in mobility patterns, and favorable meteorological conditions.

From an economic perspective, the decline in NO_2 concentrations can also be viewed as part of the gradual post-pandemic recovery process. In 2021, transportation and industrial activities had not yet fully recovered, resulting in relatively lower concentrations. Entering 2022–2023, the national economy grew by around 5% (Anas et al., 2022), accompanied by a surge in transportation and industrial activities, which drove increases in NO_2 concentrations in several regions. However, by 2024, the downward trend became evident, influenced not only by meteorological conditions but also by structural transformations such as the wider adoption of digital transportation platforms, the growth of e-commerce, and the transition to hybrid working systems all of which indirectly contributed to reducing urban transportation emissions.

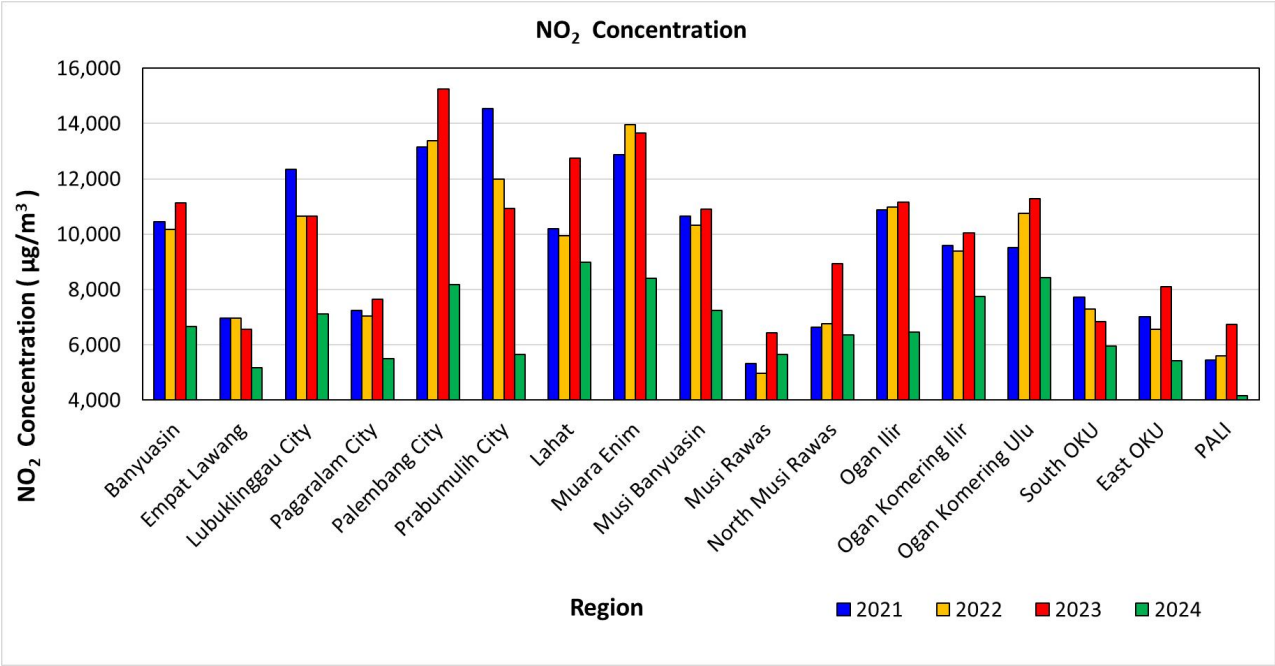


Figure 8. Trends of Average NO_2 Concentrations in South Sumatra Province Based on Passive Sampler Data from 2021 to 2024

Table 2. Annual Average NO_2 Concentrations in Districts and Municipalities of South Sumatra Province from 2021 to 2024

No	Location	Average NO_2 Concentration ($\mu g/m^3$)				Trend	Remarks
		2021	2022	2023	2024		
1	Banyuasin	10,458	10,178	11,131	6,669	Significant decrease	Fluctuating with a peak in 2023
2	Empat Lawang	6,959	6,970	6,559	5,168	Decrease	Consistently decreasing
3	Lubuklinggau City	12,355	10,648	10,641	7,119	Decreased Significantly	Consistently decreasing
4	Pagaralam City	7,244	7,034	7,645	5,498	Decrease	Insignificant fluctuation, then a decrease in 2024
5	Palembang City	13,146	13,391	15,238	8,180	Increase, then a significant decrease	Increase with a peak in 2023, then drop in 2024
6	Prabumulih City	14,531	11,998	10,923	5,641	Significant decrease	Consistently decreasing
7	Lahat	10,186	9,935	12,750	8,976	Fluctuating–increasing	Fluctuating with a peak in 2023, then a drop in 2024
8	Muara Enim	12,866	13,963	13,669	8,418	Increase, then a significant decrease	Increase with a peak in 2023, then drop in 2024
9	Musi Banyuasin	10,643	10,338	10,918	7,253	Fluctuating–decreasing	Fluctuating, then a decrease in 2024
10	Musi Rawas	5,318	4,983	6,439	5,650	Fluctuating–increasing	Fluctuating, then a decrease in 2024

No	Location	Average NO_2 Concentration ($\mu g/m^3$)				Trend	Remarks
		2021	2022	2023	2024		
11	North Musi Rawas	6,630	6,755	8,944	6,364	Fluctuating–increasing	Fluctuating with a peak in 2023
12	Ogan Ilir	10,891	10,978	11,154	6,473	Increase, then a significant decrease	Fluctuating with a peak in 2023, then a drop in 2024
13	Ogan Komering Ilir	9,603	9,396	10,054	7,749	Fluctuating–decreasing	Fluctuating with a peak in 2023, then a drop in 2024
14	Ogan Komering Ulu	9,523	10,766	11,296	8,431	Increase, then a significant decrease	Increase with a peak in 2023, then drop in 2024
15	South OKU	7,721	7,295	6,850	5,968	Decrease	Consistently decreasing
16	East OKU	7,015	6,551	8,096	5,413	Decrease	Fluctuating with a peak in 2023, then a drop in 2024
17	PALI	5,463	5,601	6,749	4,153	Increase then decrease	Increase with a peak in 2023, then drop in 2024

Implications of these findings highlight the need for a more proactive and long-term oriented air quality management strategy. Although the recorded concentrations remain below the national ambient air quality standards, seasonal fluctuations and inter-regional differences serve as a warning that economic growth and transportation expansion could significantly increase emissions if not counterbalanced by effective mitigation policies. Recommended measures include strengthening air quality monitoring systems that integrate real-time meteorological data, promoting low-emission transportation through incentives for electric vehicles and the expansion of public transport, as well as controlling emissions from fossil-fuel-based industrial sectors. In addition, the expansion of urban green spaces in cities such as Palembang can serve as natural pollutant sinks while simultaneously improving environmental quality. By implementing evidence-based policies aligned with sustainable development goals, the downward trend in NO_2 concentrations observed in 2024 can be maintained consistently, thereby supporting both public health and environmental stability in South Sumatra Province.

3.7. SO_2 Concentration in South Sumatra Province Based on Passive Sampler Data in 2021

In the first monitoring period of 2021, the median concentration of SO_2 ranged from 3.67 to 15.94 µg/m³, while in the second period it ranged from 5.52 to 13.59 µg/m³. These values remain far below both the Indonesian national ambient air quality standard (150 µg/m³, Ministry of Environment and Forestry Regulation No. 22 of 2021) and the European Union (EU) standard of 20 µg/m³. Accordingly, the air quality in terms of SO_2 concentration during this year can be categorized as good. Figure 8 illustrates the variation and fluctuation of SO_2 concentrations across periods and among the districts and municipalities in South Sumatra Province in 2021.

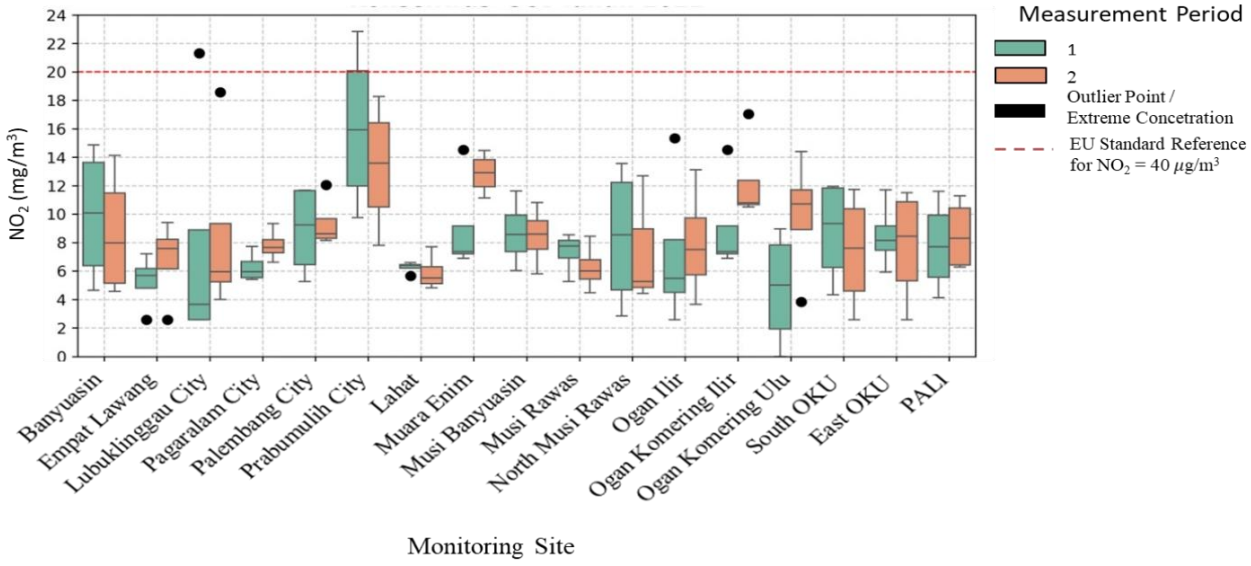


Figure 9. SO_2 Concentrations in South Sumatra Province Based on Passive Sampler Data in 2021

As shown in Figure 9, based on the median values, the height of the boxes between periods, and the length of the whiskers, six locations experienced an increase in SO_2 concentration during the second period, while other locations either decreased or remained stable. Spatially, SO_2 concentrations tended to be higher in urban areas or locations with dense industrial and transportation activities, such as Palembang City, compared to rural areas with fewer transportation and industrial activities.

This spatial pattern aligns with satellite-based emission studies indicating that elevated SO_2 concentrations and emissions are predominantly associated with urban and industrialized regions. Using high-resolution TROPOMI observations, Fioletov et al. (2020) demonstrated that major anthropogenic SO_2 point sources are closely linked to fossil-fuel combustion from transportation and industrial activities, particularly in densely populated areas. Similar urban–rural contrasts in SO_2 concentrations were also reported in the Bandung Basin during 2014–2018, where urban areas exhibited higher SO_2 levels than surrounding rural regions, further reinforcing the role of fossil-fuel-based transportation and industrial activities as dominant SO_2 sources. Furthermore, the increase observed during the second period can be attributed to the rise in activities across various sectors following the easing of pandemic restrictions in early 2021, particularly in the transportation sector. However, as office activities were still partially implementing work-from-home (WFH) arrangements, the observed fluctuations and increases were not highly significant.

3.8. SO_2 Concentration in South Sumatra Province Based on Passive Sampler Data in 2022

In 2022, during the first period, the median SO_2 concentrations ranged from 4.64 to 13.00 µg/m³, while in the second period, the values ranged from 3.89 to 12.29 µg/m³. Compared to 2021, SO_2 concentrations showed a decline, although spatial variations across districts and municipalities were still observed. Figure 9 illustrates the variation and fluctuation of SO_2 concentrations between periods and among districts/municipalities in South Sumatra Province during 2022.

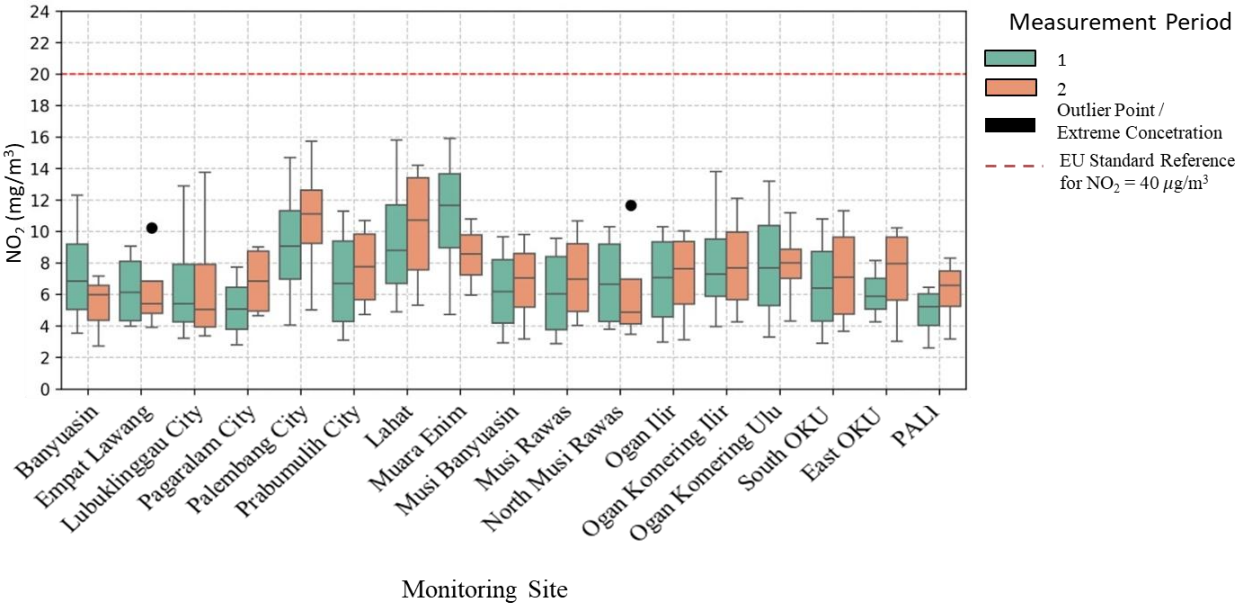


Figure 10. SO_2 Concentrations in South Sumatra Province Based on Passive Sampler Data in 2022

The fluctuation of SO_2 concentrations in 2022 was strongly influenced by the dynamics of post-COVID-19 pandemic activities. In the second period, ten locations experienced an increase in concentration, particularly in areas dominated by industrial zones. Outliers observed in the boxplot were mostly associated with industrial activities, consistent with findings that the industrial sector is one of the major contributors to SO_2 emissions alongside transportation and biomass burning (Nurhisanah et al., 2022). This supports the assumption that the rise in concentrations at several locations during the second period was driven by the resumption of human activities, especially in the industrial sector, following the end of social restrictions.

Meteorological conditions also played an important role in the distribution of SO_2. High rainfall during the first period likely contributed to lowering concentrations through wet deposition mechanisms, whereas in the drier second period, pollutants tended to persist longer in the atmosphere. This finding aligns with the analysis of Lin et al. (2023), who reported that the spatial distribution of SO_2 and NO_2 in Asia is closely correlated with both meteorological factors and anthropogenic emissions, where low rainfall and weak air circulation enhance the accumulation of pollutants in the atmosphere.

3.9. SO_2 Concentration in South Sumatra Province Based on Passive Sampler Data in 2023

In 2023, monitoring using the passive sampler method indicated that the median SO_2 concentration ranged from 4.98 to 10.79 µg/m³ during the first period and increased to 5.14 to 13.14 µg/m³ in the second period. These results demonstrate a rise in concentrations compared to 2022, particularly in the second period, as reflected by the higher median values and wider concentration ranges across monitoring sites. Figure 10 confirms the presence of more pronounced fluctuations, with the interquartile ranges and whiskers appearing higher than in the previous

year, thereby highlighting greater spatial and temporal variability among districts and cities in South Sumatra Province.

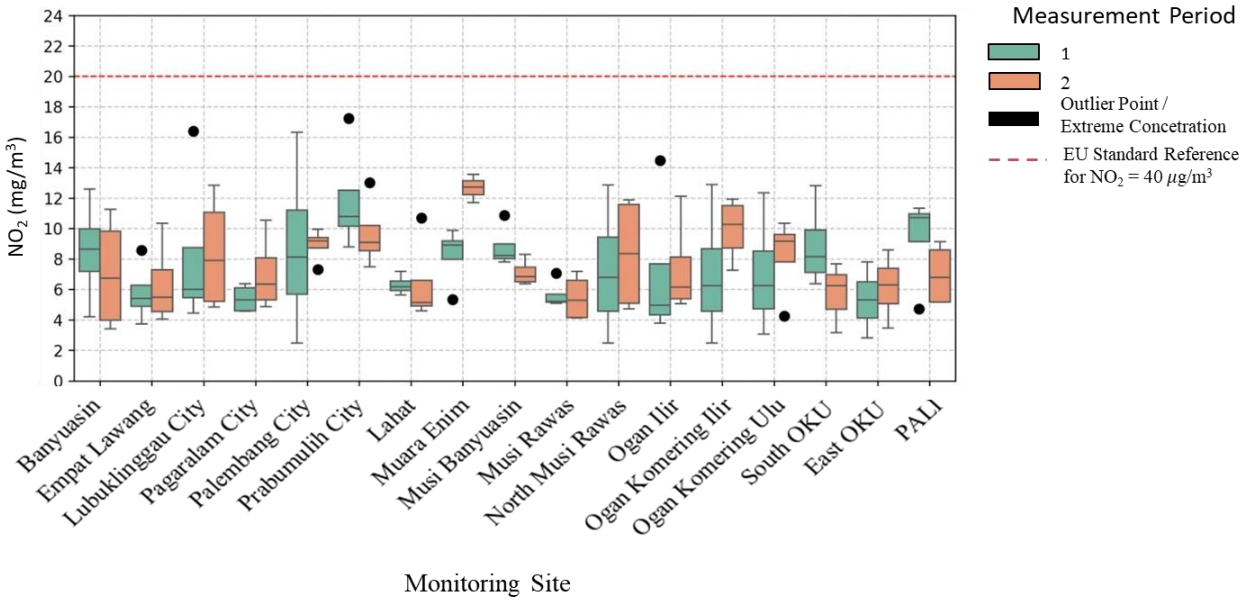


Figure 11. SO_2 Concentration in South Sumatra Province Based on Passive Sampler Data in 2023

The increase in SO_2 concentration in 2023 was strongly associated with the resurgence of activities across multiple sectors, particularly transportation and industry, in line with the recovery of economic activities after the pandemic. Furthermore, meteorological conditions played a significant role in influencing the magnitude of concentration fluctuations. Relatively lower rainfall during the second period reduced the atmospheric cleansing process (wet deposition), allowing pollutants to remain in the air for a longer duration. This pattern is consistent with the findings of Lin et al. (2023), which highlighted that variations in SO_2 and NO_2 concentrations across Asia are largely driven by the combined effects of anthropogenic emissions and meteorological factors, where lower precipitation and weaker air circulation tend to exacerbate pollutant accumulation.

3.10. SO_2 Concentration in South Sumatra Province Based on Passive Sampler Data in 2024

In 2024, the median SO_2 concentration measured using the passive sampler ranged from 5.08 to 11.65 µg/m³ in the first period and from 4.88 to 11.12 µg/m³ in the second period. These values were lower compared to 2023, indicating a downward trend following the significant increase observed in the previous year. **Figure 12** illustrates the spatial and temporal variations in SO_2 concentration across periods and among districts/cities in South Sumatra Province during 2024.

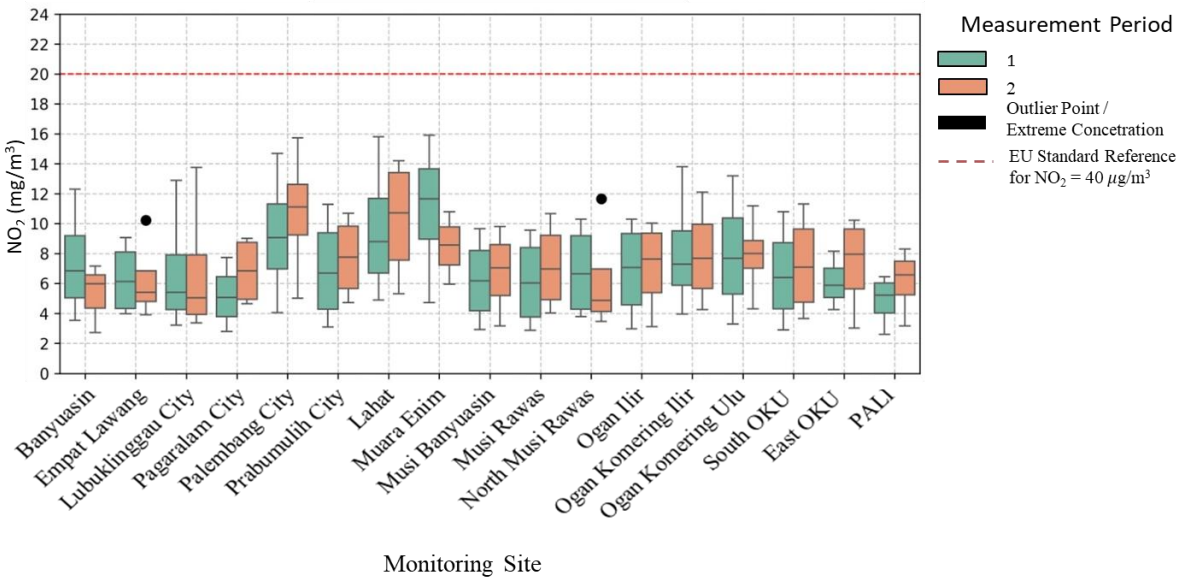


Figure 12. SO_2 Concentrations in South Sumatra Province Based on Passive Sampler Data in 2024

From Figure 12, it can be observed that the data distribution was more stable, characterized by shorter whiskers and a very limited number of outliers. This indicates a reduction in both spatial and temporal fluctuations of SO_2 concentrations across the monitoring sites. Accordingly, 2024 can be regarded as the period with relatively stable air quality within the 2021–2024 timeframe.

The lower fluctuation trend is consistent with the stabilization of socio-economic activities in the post-pandemic period, during which transportation, industrial, and office activities no longer exhibited extreme variations as seen in 2021–2023. Only seven locations experienced an increase in concentration during the second period, while the majority showed either a decline or relatively constant levels. This pattern suggests that stabilized community activities across sectors contributed to the reduced inter-period variability. The average SO_2 concentrations in South Sumatra Province for 2021–2024 are presented in Table 3.

Table 3. Recapitulation of Boxplot Values and Average SO_2 Concentrations in South Sumatra Province (2021–2024)

Year & Period	Average Concentration (µg/m³)	Outliers (Extreme Spikes)	Remarks
2021			
Period 1	4,75 - 16,12	4 upper outliers from transportation and industrial sources, 2 lower outliers from residential sources	Some exceedances of the air quality standard
Period 2	5,60 - 13,32	3 upper outliers from transportation, residential, and industrial sources, 2 lower outliers from residential sources	Within the standard
2022			
Period 1	5,28 - 12,87	5 upper outliers from transportation, office, and industrial sources, 1 lower outlier from transportation sources	Within the standard
Period 2	5,85 - 12,04	3 upper outliers from transportation and industrial sources	Within the standard
2023			
Period 1	5,32 - 11,91	6 upper outliers from industrial, transportation, and office sources, 2 lower outliers from transportation sources	Within the standard
Period 2	5,48 - 12,66	2 upper outliers from transportation and industrial sources, 2 lower outliers from transportation sources	Within the standard
2024			
Period 1	4,87 - 10,98	No upper or lower outliers	Within the standard
Period 2	5,30 - 10,75	2 upper outliers from industrial sources	Within the standard

From Table 3, it can be observed that fluctuations in SO_2 concentrations in South Sumatra Province occurred primarily during the second monitoring period using passive samplers. In 2023, the concentrations increased during the second period, while in other years they showed a decline. The second period of monitoring was conducted in July and September, when rainfall was generally lower compared to the first period, resulting in the absence of a "washing" effect on gaseous pollutants due to reduced precipitation. However, relative humidity during the second period tended to be higher than in the first. This suggests that rainfall did not have a significant impact on SO_2 concentrations.

This finding is supported by a study conducted in Surabaya, which reported a weak negative correlation between rainfall and SO_2 concentrations, with correlation values ranging from -0.118 to -0.308 (Sari et al., 2015). Similarly, research by Iramawati (2018) in the Medan Industrial Area indicated that higher humidity levels were associated with lower SO_2 concentrations, with approximately 26% of SO_2 concentration variation explained by humidity. The correlation coefficient between humidity and SO_2 concentration was found to be 0.260 (Iramawati et al., 2018), highlighting that increased humidity can contribute to the reduction of SO_2 concentrations through wet deposition processes. Therefore, although rainfall levels were low, the higher relative humidity likely contributed to the decline in ambient SO_2 concentrations.

3.11. Trends of SO_2 Concentration Using Passive Sampler in South Sumatra Province 2021–2024

Similar to the annual SO_2 concentrations, there was an increase during the second period in almost all monitoring locations. However, in 2024, a general decline in SO_2 concentrations was observed across all districts and cities. The inter-period trend is illustrated in Figure 12, which shows a consistent tendency for higher concentrations during the second period each year, although the levels varied across different locations.

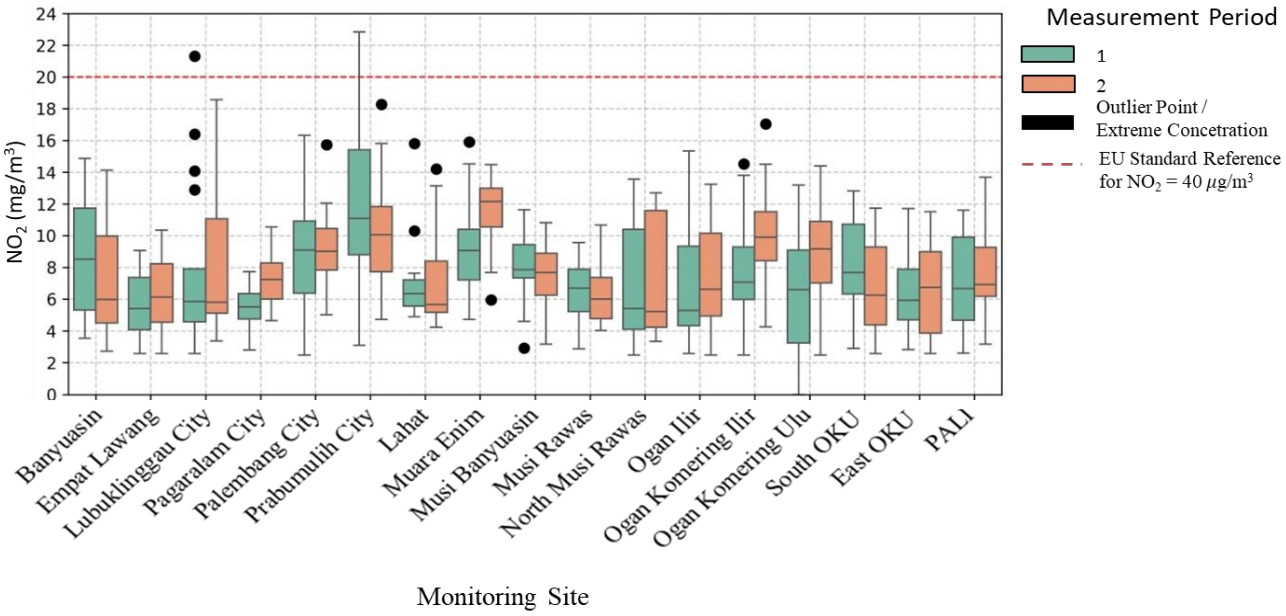


Figure 13. Inter-Period Trends of SO_2 Concentration in South Sumatra Province Based on Passive Sampler Data (2021–2024)

Based on Figure 13, the locations that showed an increase in concentration during the second period included Empat Lawang District, Lubuklinggau City, Pagaralam City, Lahat District, Muara Enim District, Ogan Komering Ilir (OKI) District, Ogan Komering Ulu (OKU) District, and OKU Timur District. Meanwhile, other locations tended to experience a decline or remained relatively stable. The graph also highlights six locations with upper outliers and two locations with lower outliers, indicating the presence of extreme concentration values. When compared to the European Union reference standard for SO_2 of 20.00 µg/m³, it is evident that several areas in South Sumatra exceeded this threshold. Figure 13 and Table 4 present the multi-year trend of SO_2 concentrations during the 2021–2024 period, obtained from passive sampler measurements and analyzed using linear regression based on average concentration data.

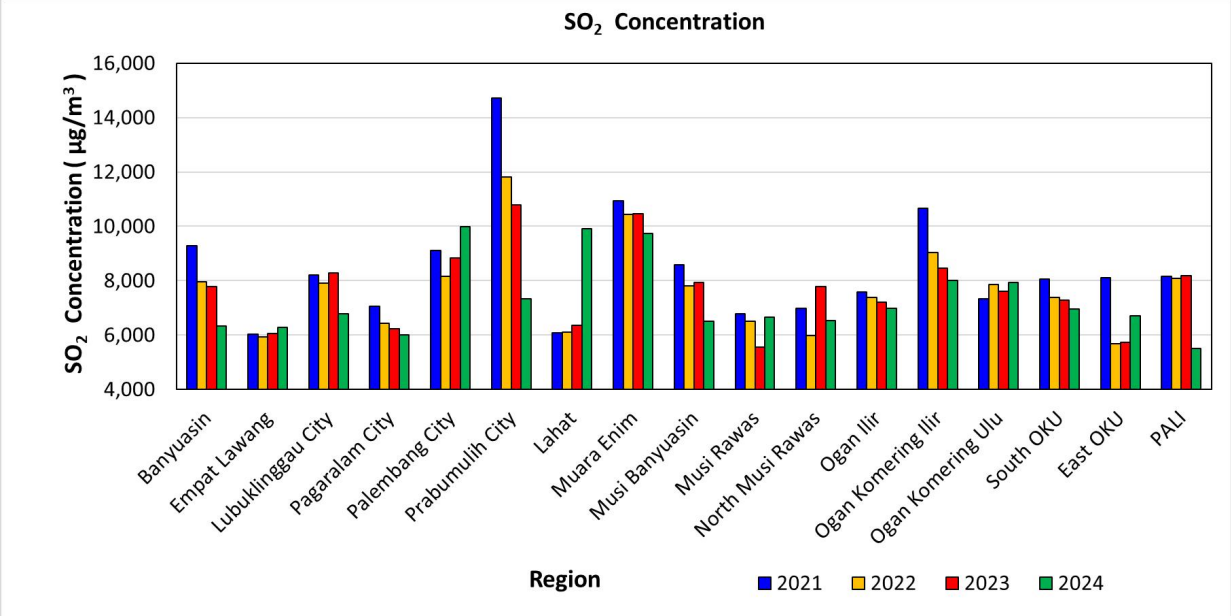


Figure 14. Trend Graph of Average SO_2 Concentrations in South Sumatra Province Based on Passive Sampler Measurements (2021–2024)

Table 4. Annual Average SO_2 Concentrations in Districts and Cities of South Sumatra Province (2021–2024)

No	Location	Average NO_2 Concentration ($\mu g/m^3$)				Trend	Remarks
		2021	2022	2023	2024		
1	Banyuasin	9,296	7,946	7,794	6,342	Decreasing	Consistently decreasing
2	Empat Lawang	6,043	5,940	6,064	6,283	Increasing	Decreased in 2022 and then increased until 2024
3	Lubuklinggau City	8,215	7,915	8,296	6,775	Decreasing	Fluctuated slightly and declined in 2024
4	Pagaralam City	7,048	6,431	6,220	6,009	Decreasing	Consistently decreasing
5	Palembang City	9,116	8,166	8,844	9,988	Fluctuating–increasing	Declined for two years, then increased in 2024
6	Prabumulih City	14,718	11,824	10,793	7,343	Significantly decreasing	Consistently decreasing
7	Lahat	6,080	6,113	6,349	9,909	Increasing	Consistently increasing
8	Muara Enim	10,948	10,428	10,463	9,728	Decreasing	Consistently decreasing
9	Musi Banyuasin	8,585	7,800	7,945	6,501	Decreasing	Consistently decreasing
10	Musi Rawas	6,786	6,510	5,566	6,653	Fluctuating–decreasing	Fluctuated and increased in 2024
11	North Musi Rawas	6,984	5,987	7,781	6,529	Fluctuating–decreasing	Fluctuated with a peak in 2023, then declined in 2024
12	Ogan Ilir	7,589	7,385	7,219	6,979	Decreasing	Consistently decreasing
13	Ogan Komering Ilir	10,658	9,024	8,461	8,014	Decreasing	Consistently decreasing
14	Ogan Komering Ulu	7,335	7,860	7,613	7,924	Fluctuating–increasing	Consistently increasing
15	South OKU	8,063	7,373	7,288	6,956	Decreasing	Consistently decreasing
16	East OKU	8,119	5,675	5,739	6,702	Fluctuating–decreasing	Fluctuated with a downward trend
17	PALI	8,168	8,085	8,181	5,514	Fluctuating–decreasing	Fluctuated with a peak in 2023, then declined in 2024

From Figure 14 and Table 4, it can be observed that SO_2 concentrations fluctuated throughout the year across all regions, although all regions experienced a decline in 2022, followed by both decreases and increases in the subsequent years.

The multi-year analysis presented in Figure 13 and Table 4 demonstrates fluctuations in SO_2 concentrations across each region during the study period. In general, nearly all regions experienced a decrease in concentrations in 2022, before showing fluctuating patterns of both increases and decreases in the following years. Based on the linear regression trend graph, most regions exhibited a declining tendency in SO_2 concentrations. However, four regions displayed an increasing trend, namely Empat Lawang Regency, Palembang City, Lahat Regency, and OKU Regency. These four areas are typically centers of economic and industrial activities, including dense transportation and combustion processes within the energy sector. For instance, in Palembang City, the high SO_2 concentration may be influenced by the presence of coal-fired power plants (PLTU) and heavy transportation activities with high vehicle volumes, including trucks and buses (Qotrunnada et al., 2025).

The primary sources of SO_2 emissions generally originate from the combustion of fossil fuels, such as coal in the energy sector and crude oil in diesel and gasoline engines in the transportation sector (Ministry for the Environment, 2021). Nevertheless, the relatively consistent downward pattern in SO_2 concentrations from 2022 to 2024 may be associated with the long-term effects of the COVID-19 pandemic, during which industrial and transportation activities had been halted or slowed, and only gradually resumed. This resulted in an uneven recovery of economic and transport activities, leading to a general decline in SO_2 concentrations in most regions. Areas dominated by plantation and service-based economies tended to experience more significant reductions compared to regions with a strong reliance on heavy industry, thereby reinforcing the close link between regional economic structures and ambient air quality.

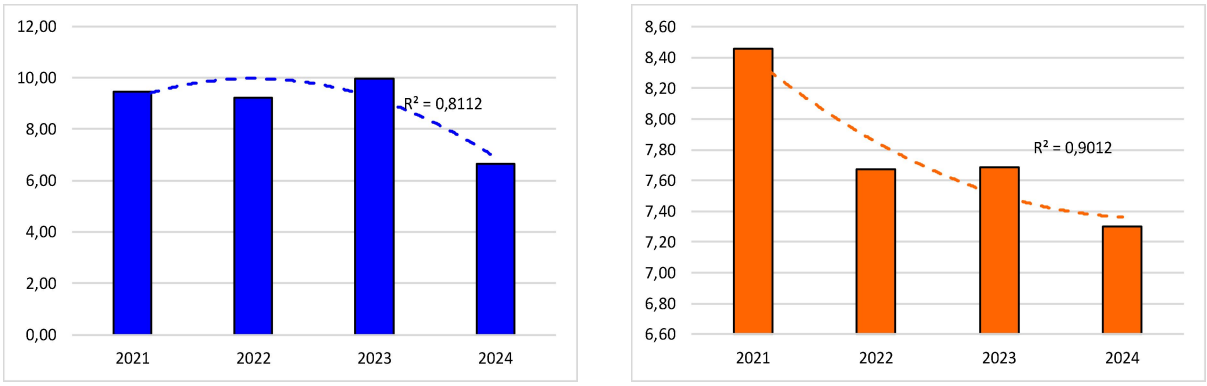
3.12. Trends of NO_2 and SO_2 Concentrations Using Passive Sampler in South Sumatra Province 2021–2024

Based on the analysis of NO_2 and SO_2 concentrations using the passive sampler method, as shown in Figure 14, both parameters exhibited a consistent downward trend throughout the 2021–2024 period. NO_2 showed a relatively significant decrease, with a coefficient of determination of $R^2 = 0.8112$, indicating that the trendline model explained the data variation very well. Meanwhile, SO_2 demonstrated an even more consistent decline with an R^2 value of 0.9012, confirming that the observed fluctuations in the field were highly explained by the trend model. Overall, the areas that experienced the greatest reductions in concentration were predominantly regions

with economies based on plantations and services, compared to regions with more intensive industrial and transportation activities.

The decrease in NO_2 and SO_2 concentrations can be linked to the long-term effects of the COVID-19 pandemic. In 2021, which marked the transitional phase following the pandemic, transportation and industrial activities had not yet fully recovered, resulting in relatively lower pollutant levels. Economic recovery and mobility resumed gradually in the following years, yet the overall downward trend in pollutant concentrations persisted. Another contributing factor was the transformation in work patterns and economic activities toward digitalization, including the adoption of hybrid and remote working systems. According to Lee (2023), the percentage of job advertisements offering hybrid or remote schemes tripled in the United States between 2020 and early 2023, and increased more than fourfold in Australia, Canada, New Zealand, and the United Kingdom. These shifts in work systems reduced the demand for daily mobility, which in turn helped suppress emissions from the transportation sector—one of the primary sources of NO_2 and SO_2.

Thus, the observed declining trend in both air pollutant parameters reflects a combination of structural factors, such as shifts in economic and transportation activities in the post-pandemic period, as well as spatial factors, where regions with non-industrial economic bases exhibited a faster decrease in concentrations. These findings are important as a foundation for formulating air quality management policies, particularly in promoting clean energy transitions and strengthening sustainable transportation systems to ensure that the reduction in pollutant concentrations can be maintained in the long term.



(a) (b)

Figure 15. (a) NO_2 Concentration Trends (b) SO_2 Concentration Trends in South Sumatra Province Based on Passive Sampler Data 2021–2024

3.13. Air Pollution Control and Prevention Strategies

Based on the observed trends of NO_2 and SO_2 concentrations in South Sumatra Province during the 2021–2024 period, several strategic approaches can be developed to support air pollution control and prevention.

First, it is necessary to strengthen the air quality monitoring system through the integration of ground-based measurements using passive samplers with satellite imagery data, such as Sentinel-5P. Previous studies have demonstrated that high-resolution satellite observations from Sentinel-5P/TROPOMI provide robust information on NO_2 and SO_2 variability at regional to urban scales and serve as an effective complement to in situ monitoring networks, especially in areas with sparse monitoring infrastructure (Levelt et al., 2022). Consistent with these findings, the correlation observed between satellite-derived data and passive sampler measurements in this study highlights the significant potential of satellite observations as complementary monitoring instruments in regions lacking continuous active monitoring stations. Such integration would enhance spatial coverage and support the development of early warning systems for the timely detection of sudden increases in pollutant concentrations.

Second, emission source control should focus on the transportation and industrial sectors, which are the primary contributors to NO_2 and SO_2 emissions. For the transportation sector, priority measures include regular vehicle emission testing, the promotion of low-emission vehicles, and the acceleration of environmentally friendly public transport development. In the industrial sector, strategies should involve the adoption of desulfurization technologies, a transition toward low-sulfur fuels, and the strengthening of regulatory frameworks and compliance monitoring. This approach aligns with the ongoing global push for a clean energy transition to reduce air pollution while simultaneously addressing climate change.

Third, forest and land fire (karhutla) management must be prioritized given its substantial contribution to increased pollutant concentrations, especially during the dry season. Strategies may include strengthening technology-based early detection systems, enhancing field patrols and surveillance, and empowering communities

to adopt zero-burning land management techniques. Additionally, stricter law enforcement against illegal burning practices is essential to ensure that fire mitigation efforts are carried out sustainably.

By integrating these three strategic approaches, air pollution control in South Sumatra Province is expected not only to reduce pollutant concentrations but also to contribute to improving public health, strengthening environmental resilience, and achieving sustainable development goals in the health and environmental sectors.

4. CONCLUSION

This study examined the trends of Nitrogen Dioxide (NO_2) and Sulfur Dioxide (SO_2) concentrations in South Sumatra Province during the 2021–2024 period based on Passive Sampler monitoring data collected from 68 sites across 17 districts/cities. The analysis revealed that the average concentrations of NO_2 and SO_2 remained below both the Indonesian National Ambient Air Quality Standards and the European Union (EU) reference values. The average NO_2 concentration ranged between 6.654–9.944 µg/m³, while SO_2 concentrations ranged between 7.303–8.456 µg/m³. The highest NO_2 concentrations were recorded in Palembang City and Muara Enim District, whereas the highest SO_2 concentrations were identified in Palembang City.

The multi-year trend demonstrated a significant decline in concentrations for both pollutants in 2024. This decline was influenced by a combination of structural and environmental factors, including the long-term impacts of the COVID-19 pandemic, which altered mobility patterns and industrial activities, as well as the transition toward digital and remote working systems that reduced emissions from the transportation and office sectors. Meteorological factors such as rainfall and humidity were also found to play a role in shaping concentration dynamics, particularly by accelerating pollutant deposition in the atmosphere.

Nevertheless, the consistent increase in concentrations during the second monitoring period of each year (dry season) highlights the influence of seasonal activities, including forest and land fires (karhutla) and low rainfall, which contribute to pollutant accumulation. Linear regression analysis produced high coefficients of determination ($R^2 = 0.8112$ for NO_2 and $R^2 = 0.9012$ for SO_2), confirming the stability of the downward trend patterns across years while reinforcing the validity of the model.

Overall, this study demonstrates that Passive Sampler-based air quality monitoring provides representative long-term data for evaluating air pollution dynamics. These findings offer a strong scientific foundation for formulating air pollution control strategies, particularly through strengthened policies in the transportation and industrial sectors, as well as in forest and land fire management. Implementing such strategies will be crucial to maintaining and further improving air quality in South Sumatra Province in the future.

5. ACKNOWLEDGEMENT

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