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Spatial–Temporal Changes in Air Pollutants in Four Provinces of Sumatra Island, Indonesia: Insights from Sentinel-5P Satellite Imagery

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Abstract: This study examined spatial–temporal variations in air pollutant levels across four provinces on Sumatra Island, Indonesia, utilizing data from the Sentinel-5P satellite equipped with TROPOMI and MODIS aboard NASA's Terra and Aqua satellites from 2019 to 2021. Sentinel-5P data, with a spatial resolution of 3.5 × 5.5 km^2 and near-daily temporal coverage, were used to analyze the nitrogen dioxide (NO^2), carbon monoxide (CO), and Aerosol Optical Depth (AOD) in North Sumatra, West Sumatra, Jambi, and Riau—regions selected for their distinct industrial, agricultural, and urban characteristics. The purpose of this study was to investigate seasonal trends, regional differences, and the impact of the COVID-19 pandemic on air pollution, aiming to provide insights for improved air quality management and policy development. The satellite data were validated using zonal statistics to ensure consistency and reliability. The findings revealed significant seasonal fluctuations in pollution, with elevated levels during the dry season, primarily due to land clearing and forest fires. Urban and industrial areas such as Medan, Pekanbaru, Jambi, and Padang consistently exhibited high levels of NO_2, primarily due to vehicular and industrial emissions. The regions affected by biomass burning and agriculture, particularly Jambi and Riau, displayed notably higher CO and AOD levels during the dry season. The COVID-19 pandemic provided a unique opportunity to observe potential improvements in air quality, with significant reductions in NO_2, CO, and AOD levels during the 2020 lockdowns. The NO_2 levels in urban centers decreased by over 20%, while the reductions in CO and AOD reached up to 29% and 64%, respectively, reflecting diminished human activities and biomass burning. This study underscores the need for enhanced air quality monitoring and targeted management strategies in Sumatra, Indonesia. Future research should aim to improve the resolution and validation of data with ground-based measurements and broaden the number of pollutants studied to better understand air quality dynamics and support effective policy development.

Keywords: air pollution; spatial-temporal analysis; Sentinel-5P satellite imagery; Sumatra Island; aerosol optical depth; COVID-19 impact; Indonesia

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1. Introduction

Air pollution, originating from particulate matter (PM) and gaseous emissions, has become a major global environmental concern in recent decades, significantly affecting human health, the environment, and economic stability [1–5]. PM, particularly PM2.5, PM10, and even PM0.1, poses severe health risks to humans, as these particles can penetrate to the deepest parts of the respiratory system, causing various respiratory diseases such as asthma, bronchitis, and even premature death [6–8]. Similar to PM, gaseous pollutants, including nitrogen dioxide (NO_2) and carbon monoxide (CO), also significantly affect human health. For instance, NO_2 exposure can exacerbate respiratory illnesses, reduce lung function, and increase vulnerability, particularly in children and the elderly [9,10]. CO, often referred to as a "silent killer" due to its colorless and odorless nature, can impair oxygen delivery in the bloodstream, leading to severe cardiovascular and neurological issues [11,12].

Since the 1980s, Indonesia has faced serious air quality issues, particularly exacerbated by forest fires in the peatlands of Borneo and Sumatra Island [13–19]. The sources of air pollution in Indonesia include both anthropogenic factors—such as vehicle emissions, industrial activities, and agricultural waste burning—and natural phenomena like volcanic eruptions and forest fires [20–25]. Urbanization and population growth have led to increased vehicle and industrial emissions, primarily affecting air quality in metropolitan areas like Jakarta. Other regions also suffer from agricultural burning, open waste burning, and occasional volcanic eruptions, contributing to the deteriorating air quality [26–30]. Sumatra Island, a major Indonesian island, experiences significant air quality degradation from these diverse sources [31,32].

The air pollution on Sumatra Island fluctuates seasonally, with increased levels during the dry season due to land clearing and forest fires [22,33,34]. This pollution not only impacts local areas but also spreads across borders, affecting other cities, provinces, and countries [35–38]. However, limited air monitoring systems in the region result in insufficient comprehensive air pollution data [38]. This issue is not confined to Sumatra; as reported by Amin et al. (2025), monitoring stations in Indonesia are highly limited, typically with only one station per province [39]. This contrasts starkly with neighboring countries such as Singapore, Malaysia, and Thailand, which maintain more extensive networks [39]. Precise and continuous air quality monitoring is crucial to support effective policy formulation and intervention strategies. The gap in ground-based monitoring underscores the need for alternative approaches, such as satellite-based remote sensing, to provide critical insights into pollution patterns.

While comprehensive air quality data are essential for developing effective pollution mitigation strategies, Sumatra and most Indonesian cities lack adequate monitoring infrastructure. The existing air monitoring infatuate, managed by the Ministry of Environment, is primarily limited to provincial capitals and does not extend to other urban or rural areas, resulting in significant data gaps [38]. Similar to other developing countries facing air pollution monitoring challenges, satellite data have emerged as a practical solution [40,41]. Satellite technologies such as MODIS, CALIPSO, GOME-2, and the recently popularized Sentinel-5 Precursor (Sentinel-5P) satellite, equipped with the Tropospheric Monitoring Instrument (TROPOMI), have been utilized [42–47]. Launched by the European Space Agency (ESA) in 2017, Sentinel-5P provides high-resolution, daily updated data and extensive coverage, including remote areas [48,49].

To address the limitations regarding air pollution data, this study employed Sentinel-5P satellite imagery to investigate air quality across sixty-five cities in four provinces—North Sumatra, West Sumatra, Jambi, and Riau—from 2019 to 2021. Additionally, it assessed the impact of the COVID-19 pandemic on air pollution in these areas by analyzing the levels of

Aerosol Optical Depth (AOD), nitrogen dioxide (NO_2), and carbon monoxide (CO). The objective was to identify patterns and trends that would establish a robust foundation for future air quality management and policy development.

2. Methodology

2.1. Study Area

The scope of this study is limited to four provinces on Sumatra Island, Indonesia, i.e., North Sumatra, West Sumatra, Jambi, and Riau. These provinces were selected due to their unique geographical and cultural characteristics, as well as their differing industrial and agricultural activities, which contribute to varied patterns of air pollution. Firstly, North Sumatra is situated in the northwestern region of Sumatra Island and is well known for its varied environmental features, including one of the most active volcanoes and extensive agricultural areas. Medan, the capital of this province, is one of the most populated cities outside of Java Island and is categorized as a metropolitan city due to its population density and industrial activities [50,51]. It plays a major role as a source of regional pollution from traffic and industry.

The second province, West Sumatra, is distinguished by its hilly topography and has experienced recent volcanic eruptions [52,53]. Compared to Medan, Padang—the capital of this province—is smaller, and the industrial activities are not as intensive. The Padang cement factory, located in the city, is one of the largest factories in the province and an important source of air pollutants, particularly particulate matter [54,55]. Furthermore, the third province, Jambi, is located in the central-eastern region of Sumatra and is mostly characterized by extensive tropical rainforests. This province is a site for oil and natural gas extraction, activities that might impact air quality [56]. Jambi also has very large peatland areas that are commonly burned during the dry season, both naturally and man-made, for land clearing [57,58]. The last province, Riau, is renowned for its significant contribution to the palm oil sector in Indonesia. The province experiences significant air pollution problems mostly due to forest and peatland fires, which are common during the dry season [59,60]. These fires frequently occur because of land-clearing for agricultural purposes [59]. Pekanbaru, the capital of this province, is smaller than Medan but larger than Padang and Jambi in terms of population density.

In total, there are sixty-five cities or locations across these four provinces, with 25 in North Sumatra, 19 in West Sumatra, 11 in Riau, and 10 in Jambi. The names and codes of these cities are summarized in Table 1 and depicted in Figure 1. The study covered the period from 2019 to 2021, including both the dry and wet seasons, to evaluate changes in air pollution trends throughout the seasons. Furthermore, since the COVID-19 pandemic affected all countries, including Indonesia, particularly in 2020, the impact of lockdowns and the decline in economic activities would have altered emission patterns at specific sites.

Table 1. Study area in four provinces in Sumatra Island, Indonesia.

Code ID	Province	City/District/Area
1	Jambi	Batang Hari
2	Jambi	Bungo
3	Jambi	Jambi
4	Jambi	Kerinci
5	Jambi	Merangin
6	Jambi	Muaro Jambi
7	Jambi	Sarolangun
8	Jambi	Tanjung Jabung Barat
9	Jambi	Tanjung Jabung Timur
10	Jambi	Tebo

Table 1. *Cont.*

Code ID	Province	City/District/Area
11	Riau	Bengkalis
12	Riau	Dumai
13	Riau	Indragiri Hilir
14	Riau	Indragiri Hulu
15	Riau	Kampar
16	Riau	Kuantan Singingi
17	Riau	Pekan Baru
18	Riau	Pelalawan
19	Riau	Rokan Hilir
20	Riau	Rokan Hulu
21	Riau	Siak
22	West Sumatra	Agam
23	West Sumatra	Bukittinggi
24	West Sumatra	Dharmasraya
25	West Sumatra	Kepulauan Mentawai
26	West Sumatra	Kota Solok
27	West Sumatra	Lima Puluh Koto
28	West Sumatra	Padang Panjang
29	West Sumatra	Padang Pariaman
30	West Sumatra	Padang
31	West Sumatra	Pariaman
32	West Sumatra	Pasaman Barat
33	West Sumatra	Pasaman
34	West Sumatra	Payakumbuh
35	West Sumatra	Pesisir Selatan
36	West Sumatra	Sawah Lunto
37	West Sumatra	Sijunjung
38	West Sumatra	Solok Selatan
39	West Sumatra	Solok
40	West Sumatra	Tanah Datar
41	North Sumatra	Asahan
42	North Sumatra	Binjai
43	North Sumatra	Dairi
44	North Sumatra	Deli Serdang
45	North Sumatra	Humbang Hasundutan
46	North Sumatra	Karo
47	North Sumatra	Labuhan Batu
48	North Sumatra	Langkat
49	North Sumatra	Mandailing Natal
50	North Sumatra	Medan
51	North Sumatra	Nias Selatan
52	North Sumatra	Nias
53	North Sumatra	Padang Sidempuan
54	North Sumatra	Pakpak Bharat
55	North Sumatra	Pematang Siantar
56	North Sumatra	Samosir
57	North Sumatra	Serdang Bedagai
58	North Sumatra	Sibolga
59	North Sumatra	Simalungun
60	North Sumatra	Tanjung Balai
61	North Sumatra	Tapanuli Selatan
62	North Sumatra	Tapanuli Tengah
63	North Sumatra	Tapanuli Utara
64	North Sumatra	Tebing Tinggi
65	North Sumatra	Toba Samosir

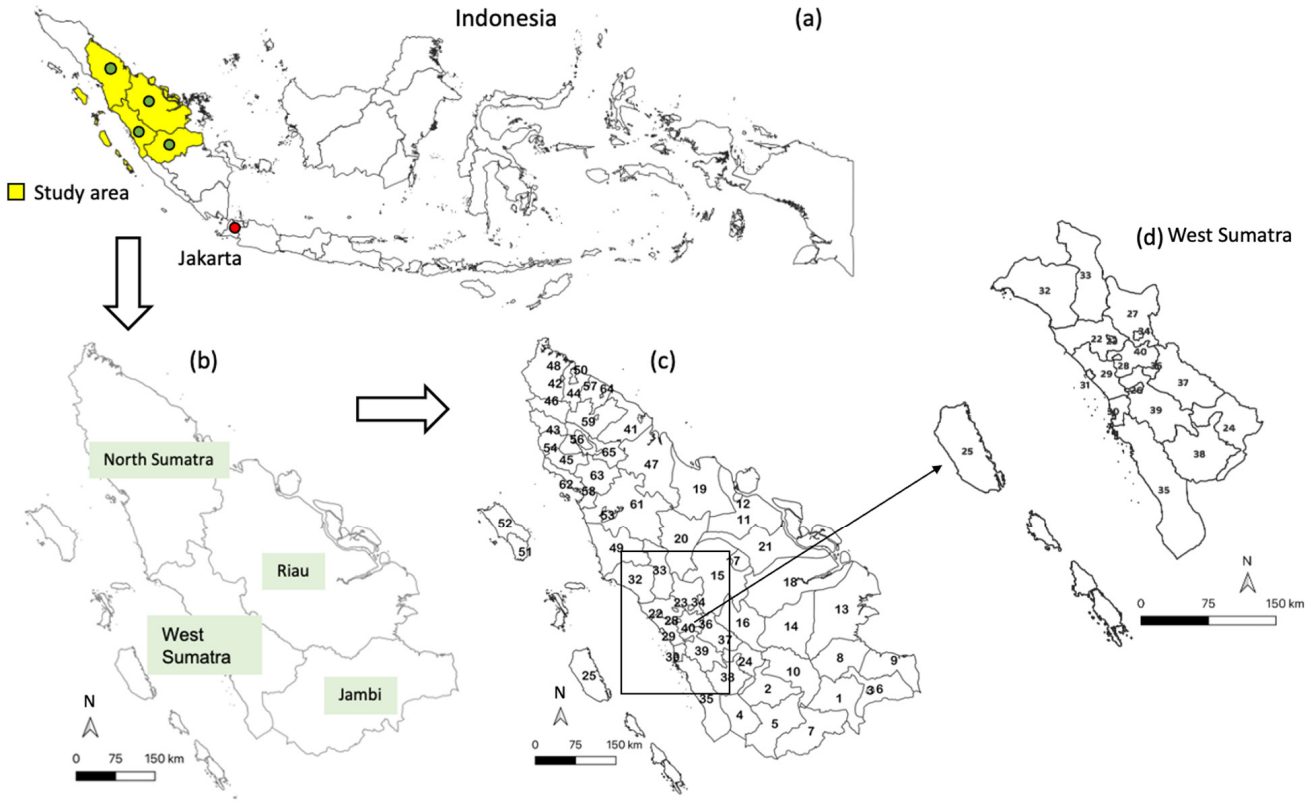

Figure 1. Maps of (**a**) Indonesian (**b**) study area in four provinces (**c**) and the 65 cities or districts in those four provinces. (**d**) West Sumatra Province, Indonesia. The numbers indicate city or district codes, and the arrows represent zoomed-in views of the study area.

2.2. Data Acquisition and Analysis

2.2.1. Data Collection

This study utilized data from the Sentinel-5P satellite, featuring the TROPOMI for monitoring NO_2 and CO concentrations [61–63]. TROPOMI operates at a spatial resolution of 3.5 × 5.5 km^2, allowing for the detection of trace gases and aerosols in the troposphere. With near-daily global coverage, Sentinel-5P is a valuable tool for large-scale air quality monitoring. The data from Sentinel-5P have been calibrated and validated by the European Space Agency (ESA), ensuring high accuracy in capturing tropospheric pollution levels. It is important to note that TROPOMI provides columnar measurements, capturing the total concentration of NO_2 and CO throughout the vertical column of the atmosphere, from the surface to the top of the troposphere. These values represent integrated atmospheric components, which may not directly correspond to surface-level pollutant concentrations.

Additionally, AOD data were obtained from the MODIS aboard NASA's Terra and Aqua satellites. MODIS provides a spatial resolution of 10 km for AOD data and captures global data on a daily basis, enabling the tracking of particulate pollution patterns. The data from MODIS are extensively calibrated and validated by NASA, making it a reliable source for studying atmospheric particulate matter loads.

All satellite data were accessed and processed using Google Earth Engine (GEE) (see Figures S1–S3), a robust platform for handling large-scale geospatial data. The outputs from GEE were in TIFF format, which were then imported into QGIS for further spatial analysis.

2.2.2. Data Processing and Analysis

Once the TIFF images were acquired, QGIS was employed to visually represent and analyze the pollutant distributions. The spatial analysis focused on converting these images into CSV format for extracting statistical data, including the minimum, maximum, mean, and median concentrations of each pollutant (NO_2, CO, AOD) across 65 districts in the four provinces of North Sumatra, West Sumatra, Jambi, and Riau. The study was structured to analyze the air quality variations across two distinct seasons from 2019 to 2021—rainy (January, November, and December) and dry (July, August and, September). This seasonal analysis aimed to capture the dynamic changes in pollution levels associated with seasonal variations in environmental conditions and human activities.

2.2.3. Statistical Analysis

The statistical processing of the data involved calculating the average concentrations of CO, NO_2, and AOD for each season, similar to methods employed in other studies. The pollutants were converted from mol/m^2 to $mmol/m^2$ and $\mu mol/m^2$ to enhance data comprehension and accuracy. Zonal statistics were used within QGIS to generate detailed reports on the pollution levels for each district, enabling a thorough evaluation of spatial variations.

2.2.4. Data Validation

Since ground-based measurements were not available for this study, we implemented a data validation process using zonal statistics to ensure the reliability and accuracy of the satellite-derived data. Zonal statistics allow for the comparison of pollutant concentrations across defined spatial zones, in this case, the 65 districts in the four provinces. This method enabled us to validate the consistency and variability of the data within each zone by calculating the coefficient of variation (CV) for each pollutant, as can be seen in the Supplementary Materials.

For CO and NO_2, the CV values were generally less than 10%, indicating consistent and reliable data across the study area. However, for AOD, the CV values were higher than 10% in some cases, particularly during the dry seasons. This higher variability is expected due to AOD's sensitivity to environmental conditions such as wind, humidity, and local aerosol emissions from biomass burning and dust storms. These factors contribute to the seasonal and spatial variability observed in the AOD data.

The use of zonal statistics for validation provides a robust approach in the absence of ground data, ensuring that the observed trends are accurate and reflective of the true spatial and temporal variations in air pollution across the study area. By calculating the CV for pollutants such as NO_2, CO, and AOD across different districts, we assessed the consistency and reliability of satellite-derived data. Although absolute values could not be validated due to the lack of ground-based monitoring, comparisons among districts and provinces support the observed seasonal and spatial patterns. The methodological workflow for satellite-based air pollution analysis in Sumatra Island is summarized in Figure 2 below.

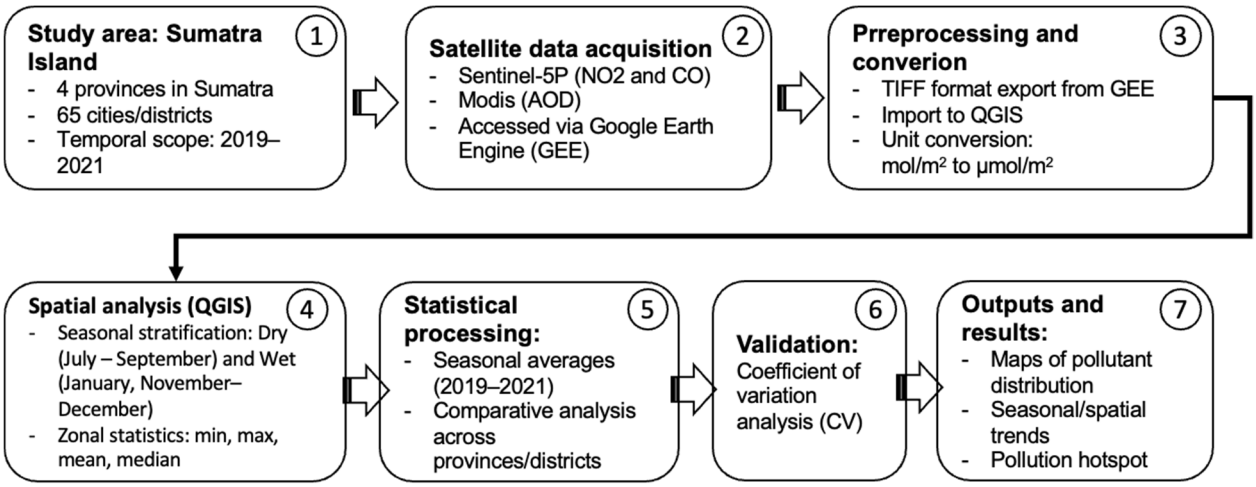

Figure 2. Flowchart of methodological phases for air pollution analysis on Sumatra Island, Indonesia.

3. Results and Discussion

3.1. Overview of Pollutants Levels

The annual pollutant levels in each district across four different provinces are illustrated in Figures 3–5 and Tables S1–S3. Overall, the data revealed significant disparities in pollutant levels, both spatially and temporally, providing valuable insights into air quality patterns in the region.

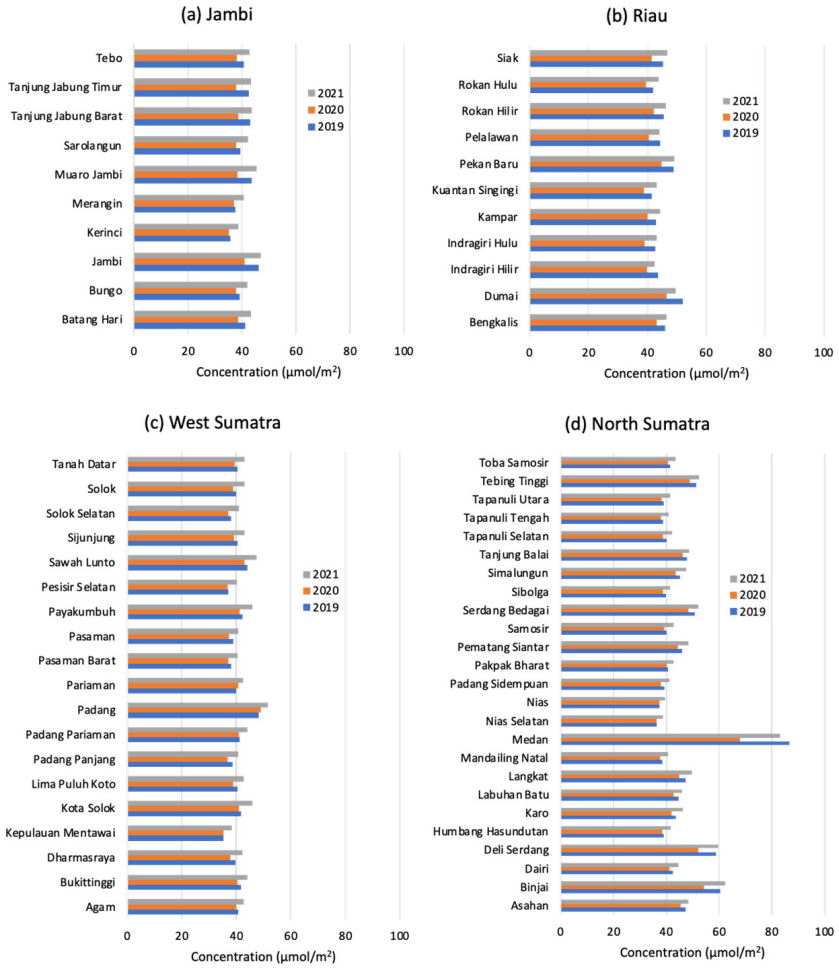

Figure 3. Annual average NO_2 concentration in (**a**) Jambi (**b**) Riau (**c**) West Sumatra, and (**d**) North Sumatra Provinces in Indonesia from 2019 to 2021.

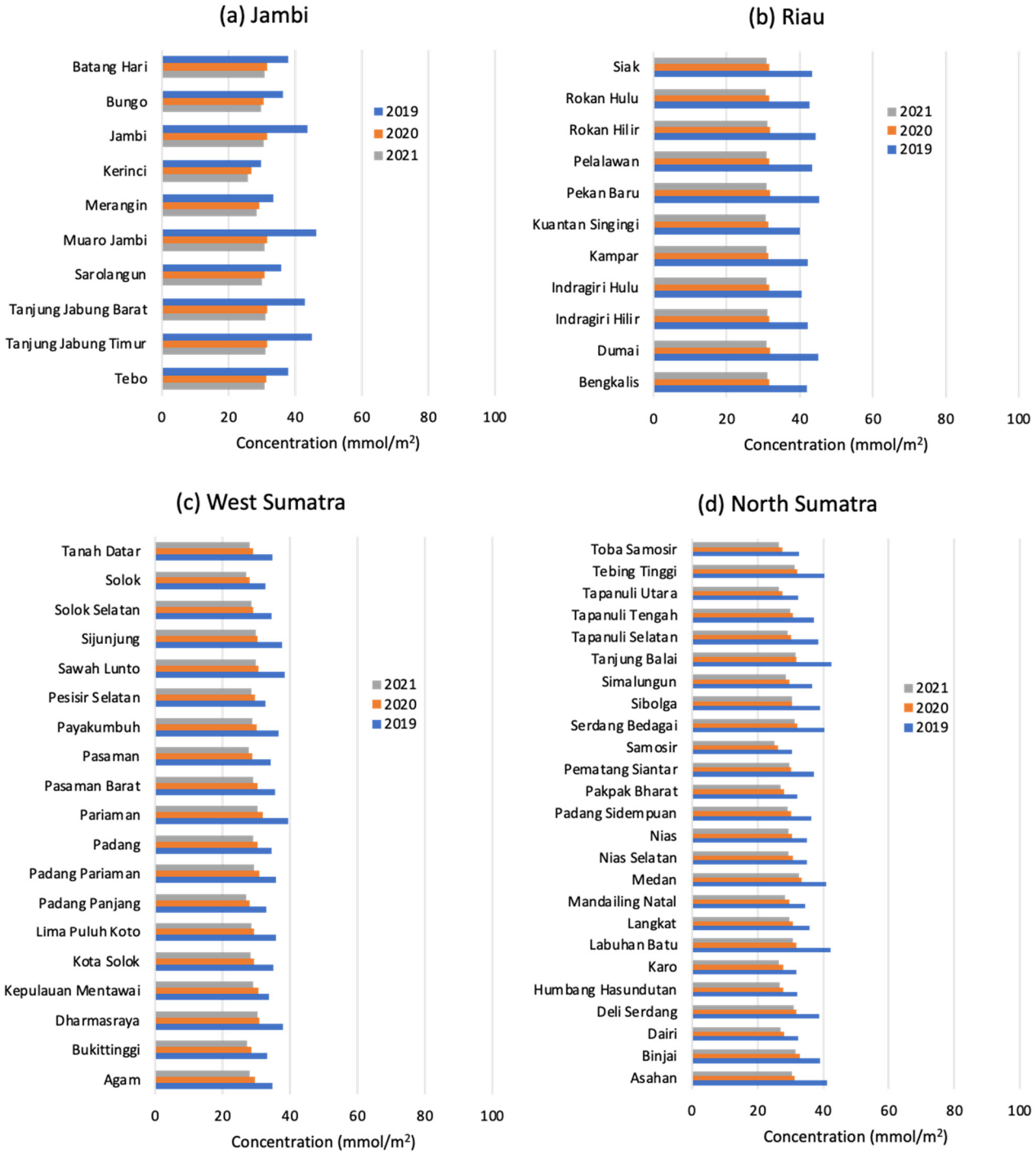

Figure 4. Annual average CO concentration in (**a**) Jambi (**b**) Riau (**c**) West Sumatra, and (**d**) North Sumatra Provinces in Indonesia from 2019 to 2021.

The NO_2 levels varied considerably, with urban and industrialized regions displaying higher concentrations compared to rural areas [64–66]. Throughout the study period, the highest NO_2 levels were observed in major cities such as Medan and Binjai in North Sumatra, Jambi City in Jambi Province, Dumai and Pekanbaru in Riau, and Padang in West Sumatra Province. Medan and Binjai, both densely populated and industrially active, consistently exhibited higher NO_2 concentrations. In 2019, Medan recorded peak NO_2 levels, with minimum, mean, and maximum values of 62.13, 86.66, and 105.48 µmol/m^2, respectively. The elevated NO_2 levels in these capital cities are likely linked to higher traffic volumes and industrial activities, which are concentrated in larger urban centers [48,67,68].

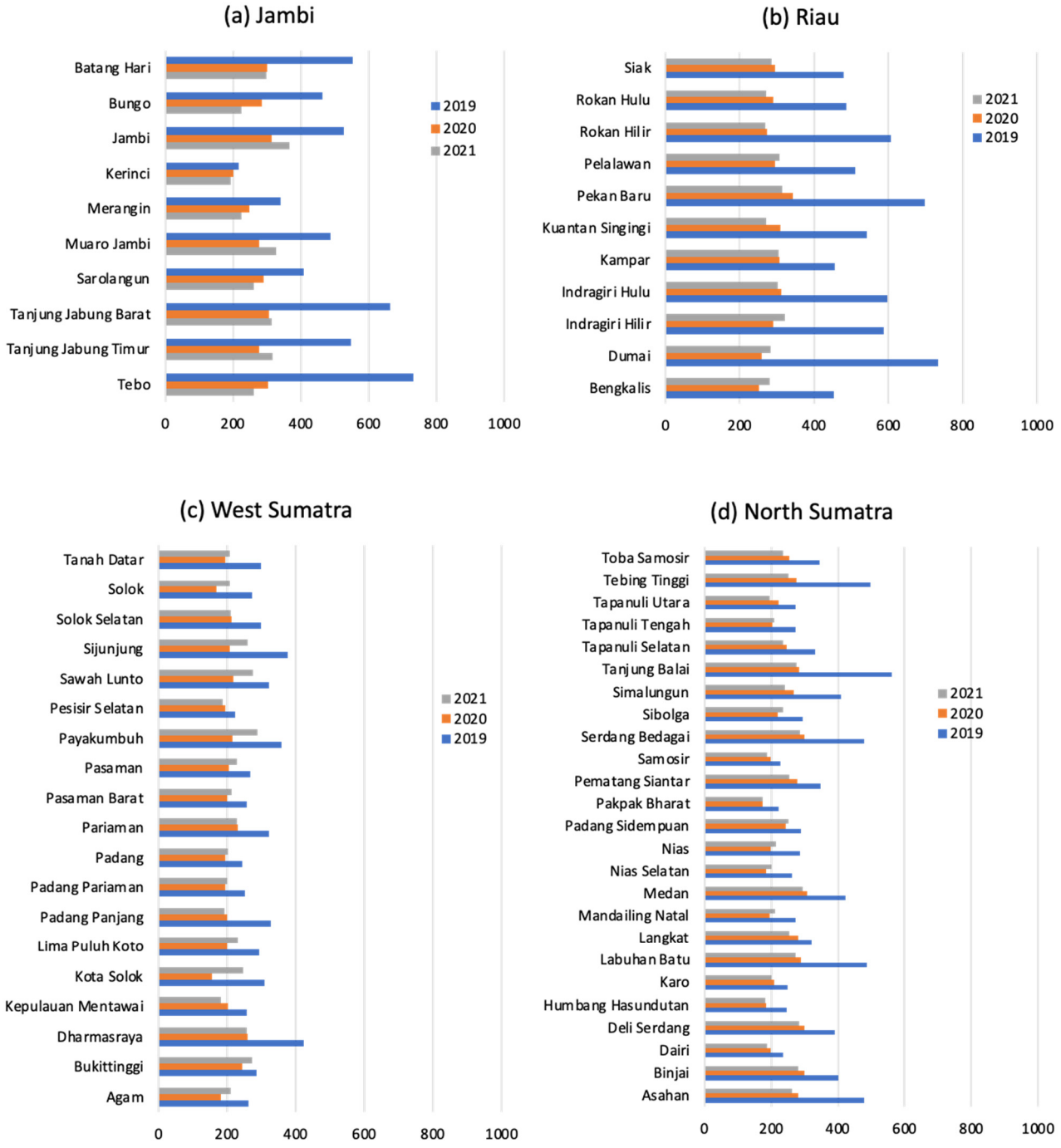

Figure 5. Annual average AOD concentration in (**a**) Jambi (**b**) Riau (**c**) West Sumatra, and (**d**) North Sumatra Provinces in Indonesia from 2019 to 2021.

The CO levels demonstrated a clear association with both traffic volume and activities like biomass burning, prevalent in both agricultural and urban settings [69,70]. During the study period, the highest CO levels were found not necessarily in the capital cities but rather in more suburban areas such as Muaro Jambi and Tanjung Jabung Timur in Jambi Province—likely related to biomass burning—and in Dumai and Pekanbaru in Riau Province, associated more with traffic. Additionally, high CO levels were recorded in Pariaman, Sijunjung, and Dharmasraya in West Sumatra Province, areas known for agriculture, as well as in Tanjung Balai and Binjai in North Sumatra Province, where both biomass burning and traffic contribute to emissions.

AOD, commonly used to measure the PM load in the atmosphere [71,72], showed the highest levels in Riau and Jambi provinces, particularly during the dry season of 2019. This may be related to forest fires, as seen in the hotspot maps in Figure 6. Both provinces experience annual forest and land fires, especially in peatlands, which emit significant amounts of aerosols [21,73]. These fires, driven by both human activities and natural factors, often occur during land clearing for new plantations [74].

To further analyze the possible impact of human activities on air quality, night-time light data from VIIRS were analyzed, as illustrated in Figure S4. Based on the figure, a clear correlation can be seen between areas of high night-time light intensity—indicative of urbanization and industrial activities—and elevated levels of pollutants such as NO_2 and CO, which are commonly emitted from vehicles, as mentioned earlier. This correlation underscores the significant influence of human activities on regional air pollution patterns.

Thus, the overview of pollutant levels highlights the substantial impact of human activities such as urbanization, industrial operations, vehicular emissions, and biomass burning in agricultural and forest areas on air pollution. Seasonal variations also significantly influence the dispersion and concentration of these pollutants. The following sections will delve deeper into seasonal variations, spatial distribution, and the specific impacts of the COVID-19 pandemic on air quality in these regions.

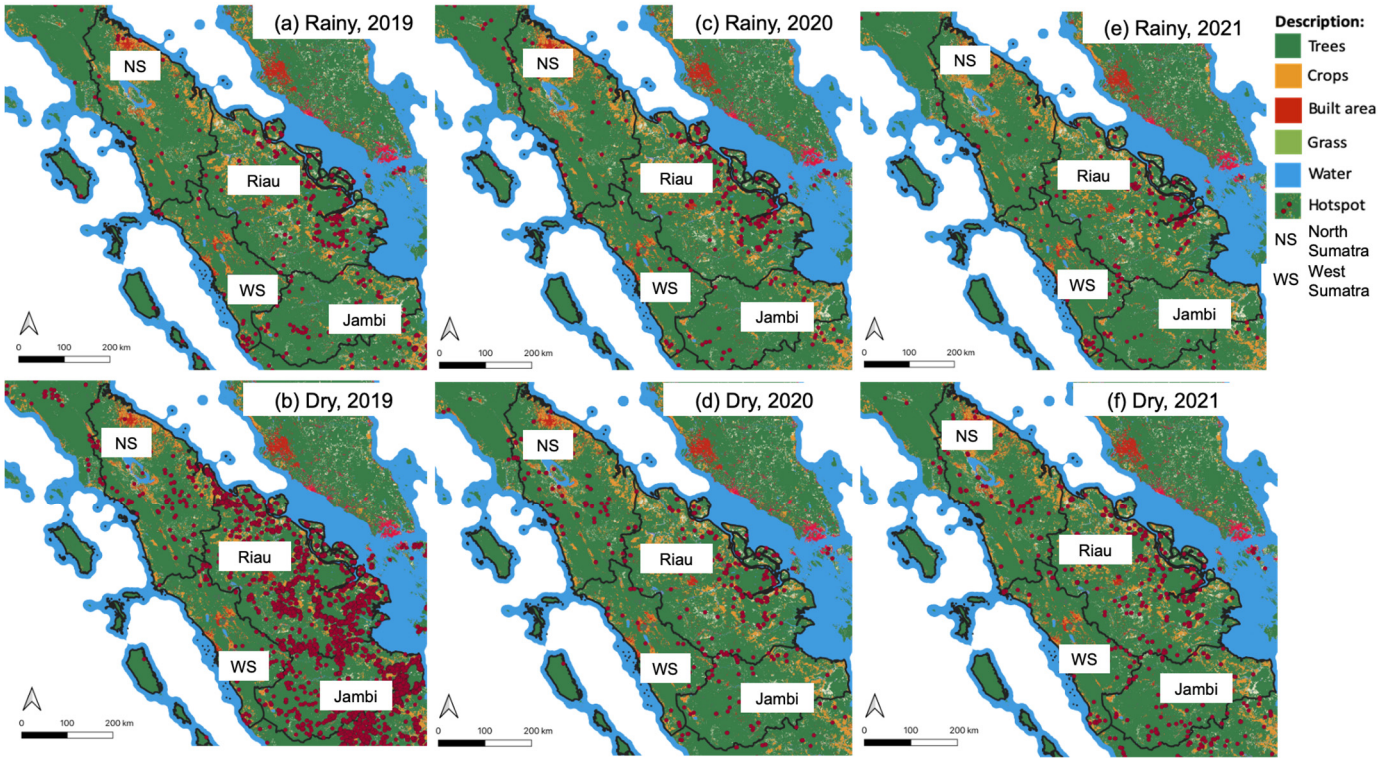

Figure 6. Land use and landcover overlap with the hotspot maps during (**a**) Rainy, 2019; (**b**) Rainy 2020; (**c**) Rainy 2021; (**d**) Dry, 2019; (**e**) Dry, 2020; and (**f**) Dry, 2021 on Sumatra Island, Indonesia.

3.2. Seasonal Variation of Air Pollutant

The spatial distribution of air pollutants across four distinct provinces in Sumatra Island is depicted in Figures 7a–f, 8a–f and 9a–f, illustrating the levels of NO_2, CO, and AOD, respectively. Each figure summarizes the pollutant levels for both the rainy and dry seasons from 2019 to 2021. The figures and tables revealed pronounced seasonal fluctuations in NO_2 levels, especially in urban areas with dense traffic and industrial activities. For example, in North Sumatra, around Medan and Binjai, the NO_2 levels were higher during the dry seasons. In 2019, the average dry season NO_2 level in Medan was

88.43 μmol/m^2, compared to 84.89 μmol/m^2 during the rainy season. In Binjai, the dry season NO_2 level in 2019 was 61.03 μmol/m^2, slightly higher than the rainy season level of 59.85 μmol/m^2. This slight increase in NO_2 levels is likely due to increased vehicular traffic and reduced rain washout. The rainy seasons generally exhibited lower levels, as wet conditions more effectively assisted in the dispersion of atmospheric pollutants [75,76]. This pattern, while less pronounced, was similarly observed in other cities across all provinces, suggesting less fluctuation in emission sources throughout the year.

The CO levels demonstrated a clear seasonal impact, largely driven by agricultural burning practices and forest fires, which are prevalent during the dry season [77,78]. In 2019, Jambi and Riau, known for their extensive agricultural lands and peatlands, experienced their highest CO levels during the dry seasons, peaking at 59.57 and 56.43 mmol/m^2 in Muaro Jambi and Tanjung Jabung Timur, respectively. In Riau, the CO levels were relatively high in the densest cities, such as Pekanbaru and Dumai, likely due to vehicular emissions, industrial activities, and the influence of transboundary haze from other regions. However, the differences in CO levels across districts within Riau were not significant, indicating that sources such as agricultural burning and peatland fires are consistent contributors across the provinces. In contrast, Riau displayed comparable CO levels across all districts, suggesting similar sources of CO emissions in this province. The reduction in CO levels during the rainy season can be attributed to the decreased occurrence of agricultural burning and forest fires, which are more common in the dry season.

The AOD levels followed a similar trend to CO, with Riau and Jambi provinces displaying more pronounced seasonal differences, especially in 2019 (See Figure 9). In 2020 and 2021, the seasonal differences were less significant, possibly due to fewer hotspots compared to 2019. The peak AOD was recorded in Tebo district during the dry season at 1161.21, being four times higher than the rainy season level of 301.75. Each province exhibited distinct patterns in pollutant concentrations, reflecting the unique environmental and industrial characteristics of each area.

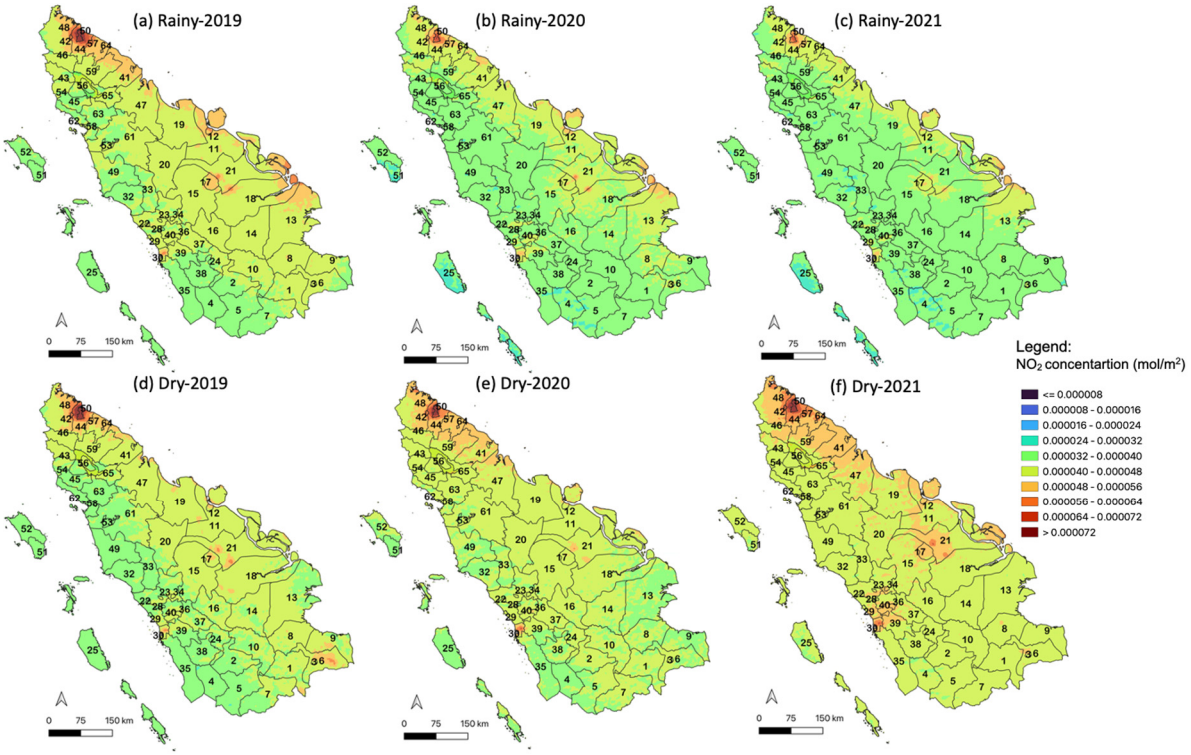

Figure 7. Spatial distribution of NO_2 in four provinces of Sumatra Island, Indonesia: (**a**) Rainy, 2019; (**b**) Rainy 2020; (**c**) Rainy 2021; (**d**) Dry, 2019; (**e**) Dry, 2020; and (**f**) Dry, 2021.

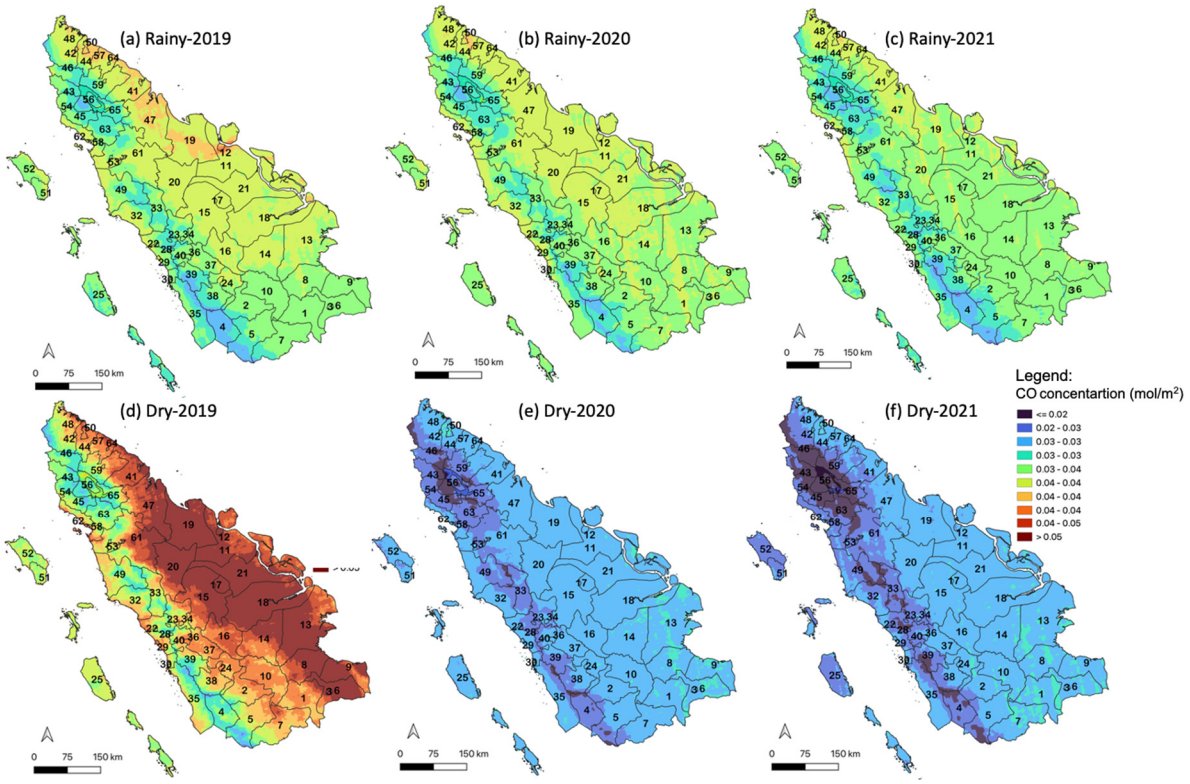

Figure 8. Spatial distribution of CO in four provinces of Sumatra Island, Indonesia: (**a**) Rainy, 2019; (**b**) Rainy 2020; (**c**) Rainy 2021; (**d**) Dry, 2019; (**e**) Dry, 2020; and (**f**) Dry, 2021.

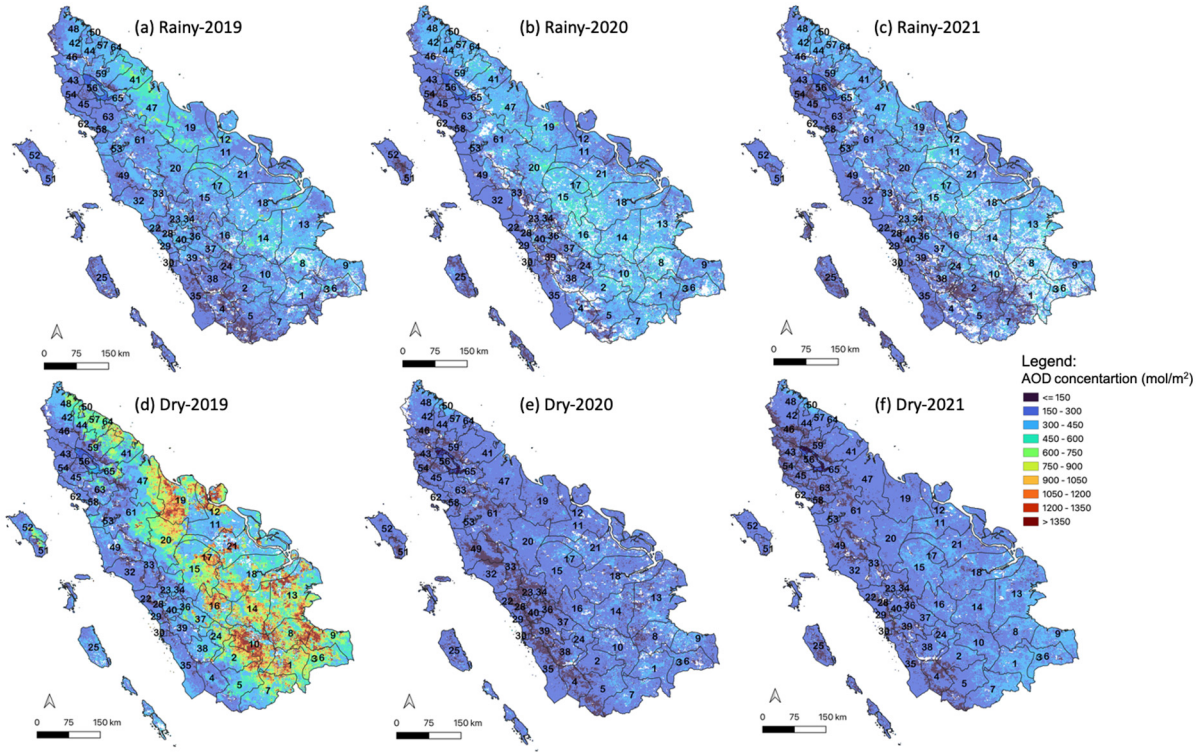

Figure 9. Spatial distribution of AOD in four provinces of Sumatra Island, Indonesia: (**a**) Rainy, 2019; (**b**) Rainy 2020; (**c**) Rainy 2021; (**d**) Dry, 2019; (**e**) Dry, 2020; and (**f**) Dry, 2021.

Furthermore, based on principal component analysis (PCA), CO consistently contributed the most to air quality variations across all seasons, explaining over 60% of the variance in each period (see Table S4). AOD and NO_2 played more significant roles in the dry seasons, reflecting the seasonal influence of biomass burning and industrial emissions. The seasonal variation is clear, with CO being dominant in both seasons but with more balanced contributions from AOD and NO_2 during the dry seasons. This highlights the impact of seasonal factors such as agricultural practices, forest fires, and meteorological conditions on pollutant levels across these provinces.

3.3. Spatial Distribution and Hotspot

The spatial distribution of pollutants across the four provinces of Sumatra Island revealed distinct hotspots where the concentrations of NO_2, CO, and AOD were consistently higher than in other regions. These hotspots are critical for targeting air quality management efforts and understanding the sources contributing to elevated pollution levels.

As illustrated in Figures 7–9, the NO_2 hotspots were located primarily in the urban and industrial areas, particularly in the capitals of each province. Medan in North Sumatra, Pekanbaru in Riau, Padang in West Sumatra, and Jambi in Jambi Province exhibited the highest levels of NO_2 compared to the other districts within each province. This correlates well with the hotspot of night-time light data from VIIRS, as shown in Figure S4 and as explained in the previous section.

The CO distribution was heavily influenced by both vehicular emissions and biomass burning [79,80]. The highest concentrations were observed in densely populated areas and regions with agricultural burning practices and forest fires, particularly in Jambi and Riau during the dry seasons.

The spatial analysis of AOD revealed that the highest readings were in districts located along the northern coast of Sumatra Island, primarily in Jambi and Riau, areas largely covered by agricultural lands and peatlands. These findings underscore the need for targeted air pollution control strategies that address specific regional sources and conditions. For instance, urban areas with high traffic emissions could benefit from improved public transportation options, while stricter emission controls and monitoring are needed in industrial areas. In agricultural and peatland regions, strategies to control biomass burning and promote sustainable land management practices are essential.

3.4. Impact of COVID-19 Pandemic

The COVID-19 pandemic significantly influenced activities worldwide and temporarily improved air quality [81–83]. On Sumatra Island, as in other parts of Indonesia, restrictions on outdoor activities led to a short-term enhancement of air quality. These restrictions resulted in decreased vehicular traffic, economic activities, and the temporary closure of street vendors and industries.

One of the major impacts of the COVID-19 pandemic on air pollutants was observed in the decline of NO_2 levels, particularly in densely populated and industrialized urban areas such as Medan, Binjai, Pekanbaru, Dumai, Padang, and Jambi. During the lockdown periods in 2020, the NO_2 levels in Medan decreased by over 20% compared to the pre-pandemic levels in 2019. Specifically, the average and maximum levels of NO_2 in Medan in 2019 were 86.66 and 105.48 $\mu mol/m^2$, respectively, which decreased to 68.02 and 78.57 $\mu mol/m^2$ in 2020, before rising again in 2021 to 83.25 and 100.60 $\mu mol/m^2$. This reduction correlates with the decline in traffic, economic, and industrial activities due to travel restrictions and temporary business closures.

Similarly, the CO levels decreased across all districts in Sumatra Island, with significant reductions noted along the northern coast in Riau and Jambi provinces. The average

reduction exceeded 20%, with the highest decreases observed in Muaro Jambi and Jambi City, at 31.83% and 27.55%, respectively, from 2019 to 2020. CO emissions arise not only from vehicle exhausts but also from biomass burning in agricultural areas.

Furthermore, AOD experienced the most substantial decrease among the pollutants during the COVID-19 pandemic. The reduction in AOD between 2020 and 2021, compared to 2019, reached up to 64%, with the most significant declines observed in Riau and Jambi provinces, mirroring the trend observed with CO levels. AOD sources include not only vehicle emissions but also agricultural and land-clearing fires, which persisted during the pandemic, particularly in regions like Riau, known for extensive peatland burning. Nonetheless, the decline in AOD resulting from decreased vehicular and industrial emissions was particularly evident in metropolitan areas.

These findings are comparable to those from Ho Chi Minh City (HCMC), where a similar satellite-based study observed reductions in various pollutants, including a significant 15.27% decline in NO_2 during the pandemic lockdown [84]. Furthermore, a study in India found comparable results, with significant reductions in NO_2 concentrations during the 2020 lockdown: −20% in Mumbai, −18% in Delhi, −14% in Kolkata, −12% in Chennai, and −15% in Hyderabad [85]. These consistent findings highlight the global impact of the COVID-19 lockdowns on air quality improvement, driven largely by the temporary reduction in human activities.

3.5. Limitation of Study

Although this research provides valuable insights into air pollutants across four provinces on Sumatra Island, several limitations must be acknowledged; these may affect the interpretation of the findings and suggest areas for improvement in future studies. The satellite data used in this study, sourced from Sentinel-5P and MODIS, offer extensive coverage but are limited by their spatial resolution. This limitation restricts our ability to identify specific pollution sources or small-scale pollution episodes, which is particularly important in urban areas where pollutant sources are densely concentrated and varied. Additionally, the lack of ground-based measurements presents a significant drawback, as ground data could have been used to validate the satellite observations. This limitation introduces uncertainties, particularly in accurately capturing surface-level pollutant concentrations. The absence of direct validation may impact the reliability of the trends observed, especially when trying to assess local pollution variations.

Future research should consider integrating satellite data with ground-based measurements, where available, to improve the accuracy of pollutant estimates. Furthermore, alternative remote sensing technologies, such as LiDAR or drone-based monitoring systems, could provide vertical profiles of pollutants, helping to address the gap left by the absence of ground-based data. Additionally, this study covered the specific period from 2019 to 2021. While this timeframe provides an initial understanding of air quality patterns, a longer-term study would offer a more comprehensive view of air pollution dynamics across Sumatra Island. Long-term data would allow for a more in-depth analysis of trends and potential shifts in pollution sources over time.

This study also focused on three specific pollutants, i.e., NO_2, CO, and AOD, and did not include other significant pollutants such as O_3 and CH_4. Including a broader range of pollutants in future research would allow for a more comprehensive assessment of air quality and its health and environmental impacts. Moreover, this study was limited to four of the ten provinces on Sumatra Island, and each province may exhibit distinct air pollution characteristics due to different industrial activities, meteorological conditions, and land use practices. By addressing these limitations in future research, the robustness of the findings can be enhanced, leading to more accurate and actionable insights for policymakers and

environmental managers. Expanding the number of pollutants studied, increasing the resolution and validation of data, and incorporating meteorological analyses are crucial steps toward achieving this goal.

4. Conclusions

This study has thoroughly analyzed the spatial–temporal changes in air pollutants across four distinct provinces on Sumatra Island, Indonesia, using Sentinel-5P satellite imagery. By evaluating the variations in NO_2, CO, and AOD from 2019 to 2021, this research provides significant insights into the dynamic characteristics of air quality when affected by both natural and anthropogenic factors. There were seasonal fluctuations in pollutant levels, with higher concentrations typically observed during the dry seasons, driven by increased land clearing and forest fires. These activities, particularly prevalent in peatland areas, significantly degrade air quality, not only locally but also in neighboring regions due to transboundary pollution spread. Urban and industrial areas, especially in larger cities like Medan, Pekanbaru, and Padang, consistently showed elevated levels of NO_2, underscoring the impact of vehicular emissions and industrial activities on air pollution.

The study also highlighted the variability in CO and AOD levels, which are heavily influenced by biomass burning and agricultural activities, particularly in provinces like Jambi and Riau. These provinces experienced the highest levels of CO and AOD during the dry seasons, correlating with the practice of land clearing through burning, especially in the peatland areas common in these regions. During the dry season in 2019, the CO levels peaked at 59.57 mmol/m^2 in Muaro Jambi and 56.43 mmol/m^2 in Tanjung Jabung Timur, reflecting the influence of agricultural burning and forest fires. Similarly, the NO_2 levels in Medan during the dry season reached an average of 88.43 μmol/m^2, highlighting the impact of vehicular emissions and industrial activities. Urban and industrial areas, especially Medan, Pekanbaru, and Padang, consistently showed elevated NO_2 levels, with Medan recording peak NO_2 values of 105.48 μmol/m^2 in 2019. These findings underscore the significant contribution of urban traffic and industrial activities to air pollution in major cities.

The pandemic lockdowns provided a unique insight into how reductions in human activity could lead to significant improvements in air quality. Medan, for example, experienced a more than 20% reduction in NO_2 levels during the 2020 lockdowns compared to pre-pandemic levels in 2019, demonstrating the direct impact of reduced traffic and human activities.

Despite these insights, this study faced several limitations that could influence the applicability of the results. The reliance on satellite data, while beneficial for broad coverage, posed challenges due to its limited spatial resolution, which could obscure the details of pollution sources and small-scale pollution episodes. Moreover, this study focused on three specific pollutants (NO_2, CO, and AOD) and four provinces, which does not cover all air quality issues across the entire island or the diverse types of pollutants affecting the region.

For future research, enhancing the detail and precision of data through integration with ground-based measurements could validate and enrich the satellite observations, providing a more detailed and accurate assessment of air quality. Expanding the scope of the study to include additional pollutants (e.g., O_3 and CH_4) and covering more provinces on Sumatra Island would offer a more comprehensive view of the regional air pollution landscape. Additionally, extending the timeframe of data collection would allow for an analysis of long-term trends and the effectiveness of air quality management strategies implemented over time.

Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/urbansci9020042/s1, Table S1: Annual mean and maximum NO_2 levels in four provinces of Sumatra Island, Indonesia, from 2019 to 2021; Table S2: Annual mean and maximum CO levels in four provinces of Sumatra Island, Indonesia, from 2019 to 2021; Table S3: Annual mean and maximum AOD levels in four provinces of Sumatra Island, Indonesia, from 2019 to 2021; Table S4: Principal Component Analysis (PCA) results for CO, AOD, and NO_2 across seasons from 2019 to 2021; Figure S1: Program code using Google Earth Engine (GEE) for AOD retrieval; Figure S2: Program code using Google Earth Engine (GEE) for NO_2 retrieval; Figure S3: Program code using Google Earth Engine (GEE) for CO retrieval; Figure S4: Comparison of night-time light (VIIRS) and NO_2 concentrations from 2019 to 2021 in four provinces of Sumatra Island, Indonesia.

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