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Original Research Article

PM$_{2.5}$ Temporal Pattern in Jambi City: Meteorological Drivers and Air Mass Trajectory Analysis

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Abstract

Air pollution, particularly particles with diameter of less or equal than 2.5 micrometers (PM$_{2.5}$), has become important global health and environmental problem. Jambi City in Sumatra is highly susceptible to this issue, both locally and particularly influenced by forest fires. As early studies were conducted over a short period, this study examined the meteorological factors that influenced PM$_{2.5}$ levels and estimated the pollutant transport pathways over two years in the post-COVID-19 period (2023-2024). The methods employed were time-series analysis, scatter-plot evaluation, multiple linear regression analysis, and backward trajectory modeling using HYSPLIT. The results show that the average PM$_{2.5}$ concentration in 2023 (30.53 µg/m^3) was higher than in 2024 (25.36 µg/m^3), with night-time levels generally exceeding day-time levels. 3.69% of the days exceeded Indonesia's daily air quality standard, while 90.83% surpassed the stricter WHO guideline. Meteorological factors explained only 23–38% of PM2.5, with temperature positively correlated, wind speed showing mixed effects, and humidity and rainfall negatively correlated.. The major PM$_{2.5}$ sources influenced by the southeast–South Sumatra, particularly South Sumatra, highlighting the strong stimulus of transboundary emissions alongside local sources. In the future, studies focusing on chemistry-based source apportionment are needed to accurately separate each contributing source.

Keywords: Forest Fires, Meteorological Factors, PM$_{2.5}$, Temporal Pattern.

1. Introduction

Urban air pollution, particularly fine particles (PM$_{2.5}$) with an aerodynamic diameter of less than or equal to 2.5 micrometers, has become a pressing global issue (United Nations, 2015; WHO, 2021). Long-term PM$_{2.5}$ exposure contributed to approximately 4.1 million premature deaths in 2019 (WHO, 2021; Health Effects Institute, 2020), with more than 90% of the population continuing to live in areas where PM$_{2.5}$ levels exceed the recommended level (Landrigan et al., 2018; Hammer et al., 2020). Recent studies have linked PM$_{2.5}$ exposure to cognitive decline and sleep disorders, indicating its broader systemic health effects (Sangkham, 2024). Moreover, prolonged exposure strongly increases the risk of cardiovascular diseases, stroke, chronic obstructive pulmonary disease (COPD), lung cancer, and adverse birth outcomes, such as preterm birth and low birth weight (Krittanawong et al., 2023; Parasin et al., 2024). Beyond health implications, excessive $PM_{2.5}$ exposure reduces visibility and disrupts daily activities such as transportation (including aviation, freight delivery, and road travel) and tourism, resulting in substantial economic losses (World Bank Group, 2021; Hao et al., 2021).

In Indonesia, air pollution has become a growing concern, especially in densely populated cities that are frequently exposed to multiple sources. The dominant contributors are vehicular exhaust and industrial activities, while biomass burning has also been identified as a critical source. Pollutant release into the atmosphere is influenced by many factors, and meteorological factors can regulate pollutant dispersion, movement, chemical transformation, and deposition (Wang & Ogawa, 2015; Nguyen et al., 2017; Chen et al., 2019; Qonita et al., 2025; Hutauruk et al., 2020). Identifying $PM_{2.5}$ pollution sources is important because the emissions are not only from the local scale but also from outside as transboundary pollutants. Therefore, cities in the Sumatra and Kalimantan islands (Indonesia) are connected to this problem, which has increasing hotspots during dry seasons due to biomass burning, influencing the ambient air levels each year.

Despite numerous studies on $PM_{2.5}$ associated with meteorological influences and potential transboundary sources in regions such as China, Europe, and North America, research in Southeast Asia is comparatively limited. Existing investigations often emphasize large metropolitan areas such as Jakarta, Bangkok, Hanoi and Kuala Lumpur (ASEAN, 2016). However, Southeast Asia, including Indonesia, is also recognized as a hotspot of transboundary haze pollution due to recurrent seasonal forest fires, particularly on the islands of Sumatra and Kalimantan (Koplitz et al., 2017; Kiely et al., 2021; Putra et al., 2023). Jambi Province was identified as an important hotspot location, along with South Sumatra and Riau in Sumatra, which influenced each other and the surrounding areas, driven by meteorological patterns. Therefore, this phenomenon needs to be observed in long-term temporal data to understand the $PM_{2.5}$ pattern and factors explained.

The city of Jambi is highly vulnerable to air pollution (Handika et al., 2023; Amin et al., 2021), with the annual average $PM_{2.5}$ concentration exceeding the Indonesian national standard of 15 μg/m³. The situation dynamically changed during the pandemic (2020–2021), with approximately 63% of $PM_{2.5}$ concentration measurements meeting the WHO standards, while around 100% of $PM_{2.5}$ concentrations prior to the pandemic (2018–2019) exceeded the WHO guidelines (Handika, et al., 2024). Regional assessments have estimated that long-term exposure to PM2.5 contributes to nearly 900,000 premature deaths annually in Southeast Asia (Yorifuji et al., 2015; Shi et al., 2018). However, city-level studies that integrate temporal analysis, meteorological variability, and long-range air mass trajectory modeling, particularly in the post-COVID 19 period. This study focused on examining the temporal patterns of $PM_{2.5}$ in Jambi City, particularly in the new normal era of post-COVID-19, based on Presidential Decree Number 17 of 2023, which started in 2023. These analyses can serve as one of the initial works that can be used for formulating policies that address air quality issues resulting from forest and land fires (such as during El Niño) in the future. This study can also provide scientific and practical contributions to air quality management at both local and regional levels.

2. Methods

2.1. Study location

The study was conducted in Jambi City, located at coordinates 1°35′24″S and 103°36′36″E, with a population of approximately 635,101 inhabitants and temperatures in the range of 23°C to 33°C (BPS, 2025). The topography is generally low-lying and flat, with elevations between 10 and 60 m above sea level. Besides being an administrative city and province, the city functions as the commercial and educational hub of the province, with a growing urban footprint and increasing anthropogenic emissions. The climate is categorized as a monsoonal type 2 climate, with two primary seasons: dry (June–September) and rainy

(November–March) (BMKG, 2022). Transition periods (April–May, October) often exhibit unstable meteorological conditions with sporadic rainfall and variable winds, which can influence pollutant build-up.

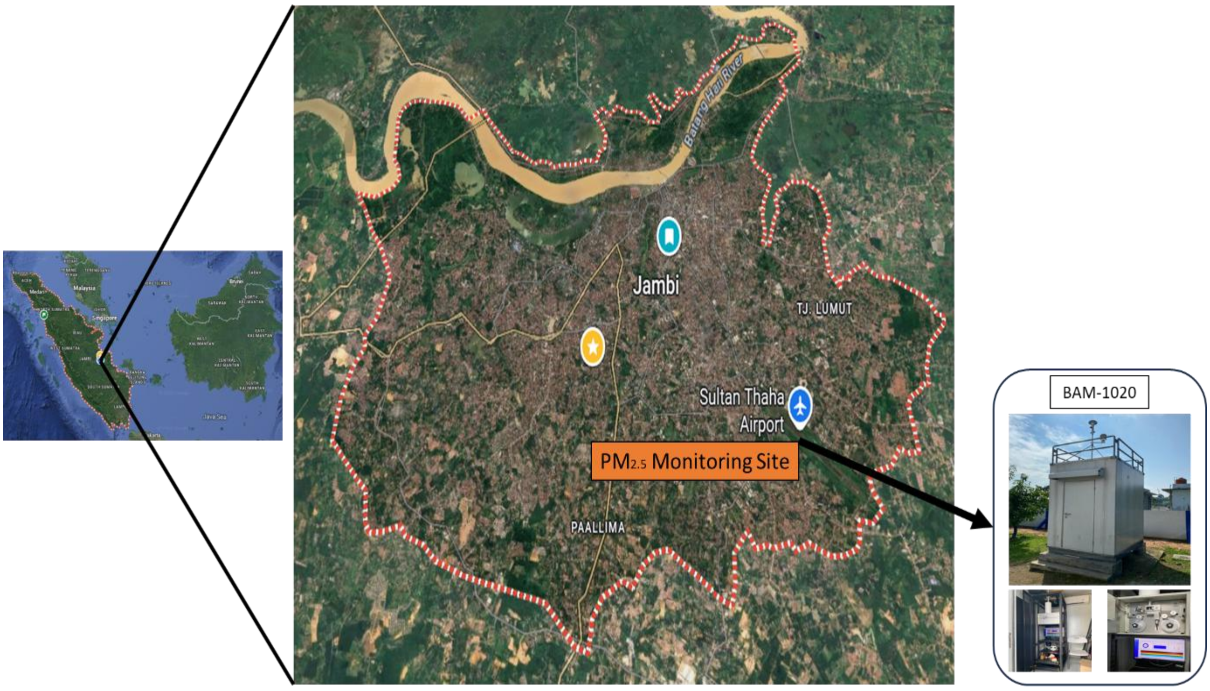

Figure 1. $PM_{2.5}$ monitoring site in Jambi City

2.2. Data collection and preprocessing

The dataset covers a two-year period, from January 2023 to December 2024, representing $PM_{2.5}$ dynamics during the post-COVID-19 situation. These data were obtained from the regular fixed-site monitoring station of $PM_{2.5}$ using a Beta Attenuation Monitor (BAM-1020, Met One Instruments, USA) operated by the Meteorology, Climatology, and Geophysics Agency of Indonesia (BMKG), located near the Sultan Thaha Airport of Jambi (**Figure 1**). The station is situated in a mixed residential–institutional area with moderate traffic influence, representing urban background air quality conditions with minimal direct interference from local point sources. The BAM-1020 is a U.S. EPA Federal Equivalent Method (FEM) for continuous $PM_{2.5}$ mass measurement, which provides reliable hourly averaged concentrations (Shukla & Aggarwal, 2022; Bai et al., 2020). Daily meteorological data, including humidity, air temperature, and rainfall, were collected for the same period. These data were sourced from the BMKG at the same station location. Several steps were involved in data processing, including the impact of extreme events and days with high concentrations due to haze events. This processed $PM_{2.5}$ dataset served as the foundation for assessing temporal variability, meteorological drivers, and regional transport influences, which are explored in the subsequent sections.

In this study, seasonal grouping was conducted based on the ten days rainfall amount. The grouping was proposed to categorize the research data based on the seasons in Jambi, defined according to the BMKG regulations, utilizing data on daily accumulated rainfall over a ten-day period. A month is divided into three ten-day periods: the first ten-day period (the 1st to the 10th of the month), the second ten-day period (the 11th to the 20th of the month), and the third ten-day period (the 21st to the end of the month). The dry season was determined if there were at least three consecutive ten-day periods with rainfall less than 50 mm per period. Based on this criterion, the dry season in Jambi runs from June to September. Conversely, the wet (rainy) season was determined if there were at least three consecutive ten-day periods with rainfall equal to or greater than 50 mm per period. The wet season runs from November to March. The transition periods (April–May and October) do not meet the rainfall criteria for either the wet or dry seasons. These periods are characterized by unstable meteorological conditions with sporadic rainfall and variable winds that can influence pollutant accumulation.

2.3. Air mass trajectory analysis

Trajectory analysis identified areas as sources of particulate pollution affecting Jambi City. The Hybrid Single-Particle Lagrangian Integrated Trajectory (HYSPLIT) transport model was used, with Global Data Assimilation System (GDAS) meteorological data with a spatial resolution of 0.5 ° × 0.5 °as the main input data, which is readily available in the HYSPLIT system (Handika et al., 2019). The GDAS is a system used to place observational data into a model-recognizable grid format so that it can be used for initial data, starting, or performing weather forecasting using the model. In its analysis process, the HYSPLIT model integrates the movement of pollutant particles based on the wind field and calculates the dispersion and deposition (wet and dry) of pollutants over a certain period. The output of this analysis visually shows where $PM_{2.5}$ originates from a given location, thereby allowing the identification of potential sources and guiding mitigation measures. The specific time chosen for this analysis was when the $PM_{2.5}$ concentration values reached their maximum for each seasonal period. This approach was based on the use in a previous study by Melinda and Nuryanto (2023). Moderate Resolution Imaging Spectroradiometer (MODIS) satellite remote sensing imagery served as an indicator of biomass burning or hotspots. The relationship between hotspot occurrence and PM2.5 characteristics was quantified and analyzed. The MODIS satellite imagery data (hotspots) used in this study were when $PM_{2.5}$ concentration values reached their maximum for each seasonal period. If the HYSPLIT trajectory passes through an area with high hotspots, it can be estimated that the region is the main source of $PM_{2.5}$ reaching Jambi.

2.4. Statistical and data analysis

Time series analysis aims to identify the temporal patterns (diurnal/12-hour, daily, and seasonal) of $PM_{2.5}$ concentrations throughout the 2023-2024 observation period by observing the temporal fluctuations, identifying the peak concentration times, and recognizing periodic seasonal trends. Furthermore, descriptive statistical analysis and data exploration using a scatter plot were employed to visually depict the relationship between the two quantitative variables. By observing the patterns of the points on the scatter plot, it is possible to identify whether there is a positive, negative, or no relationship. Furthermore, multiple linear regression analysis was performed to identify and measure the extent to which air temperature, humidity, and rainfall influenced $PM_{2.5}$ concentrations (Turyanti, 2011; Qonita, et al., 2025).

3. Result and Discussion

3.1. Temporal $PM_{2.5}$ variation during 2023-2024

Fluctuations in concentrations over 2023-2024 were analyzed to identify the $PM_{2.5}$ temporal patterns in Jambi City, both daily and seasonally. The $PM_{2.5}$ concentrations in 2023 were generally higher than those in 2024, with the annual average concentrations of 30.53 μg/m³ (2023) and 25.36 μg/m³ (2024). These values are far beyond the annual limits set by the WHO (5 μg/m³) and Indonesian Government Regulation (15 μg/m³). **Figure 2** shows a comparison of the daily $PM_{2.5}$ averages to provide an initial overview of the periods with high potential $PM_{2.5}$ concentrations. In 2023, the pattern of daily $PM_{2.5}$ concentration indicated a relatively stable condition from January to mid-August (8 μg/m³ – 53 μg/m³), while a very sharp and significant spike started in September 2023, and the highest concentrations occurred in October (69 μg/m³ - 116 μg/m³). These levels were mostly above the daily WHO guideline value of 15 μg/m³ (WHO, 2021), which caused the $PM_{2.5}$ levels to soar far above the Indonesian national standard (55 μg/m³). The pattern of daily $PM_{2.5}$ concentrations in 2024 showed much lower and more stable values, resulting in daily concentrations (7–56 μg/m³) that were mostly still below the national standard. However, in October 2024, it still reached the highest peak value of 56 μg/m³, showing during the dry season, particularly September-October, with a high number of hotspots in the Sumatra region, which could affect the particulate matter concentration levels in Jambi City.

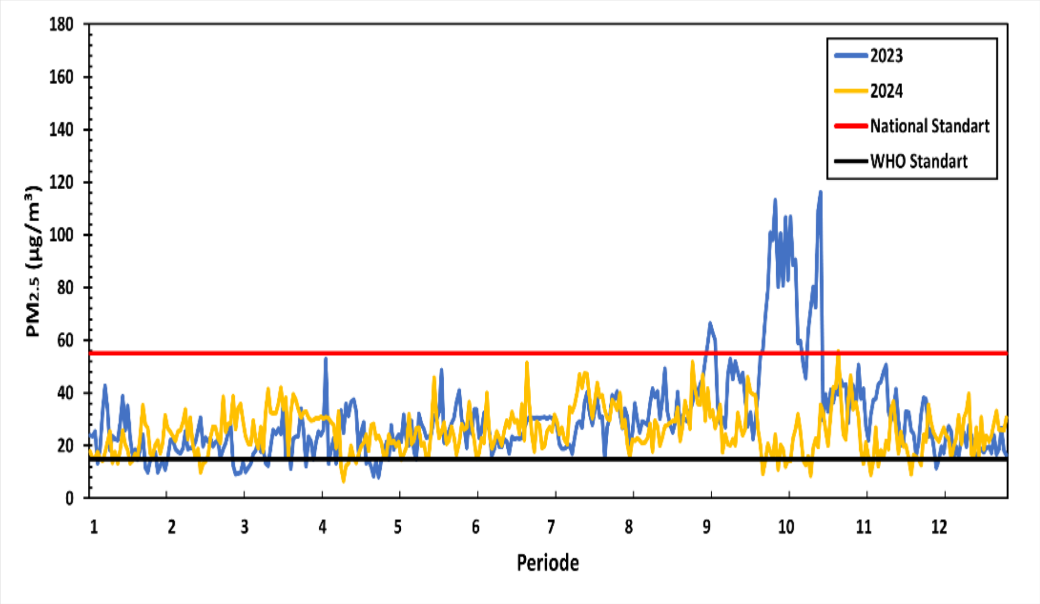

Figure 2. The daily average of $PM_{2.5}$ concentration in Jambi City during 2023-2024

Results from the post-COVID-19 analysis (2023–2024) indicate that the $PM_{2.5}$ concentration in Jambi City has increased again compared to in the COVID-19 period (2020–2021). Handika et al. (2024) also found that $PM_{2.5}$ concentrations during COVID-19 ranged between 19.48 - 35.83 µg/m³, suggesting that the normalization of community activities (particularly in the transportation and industrial sectors) has become the main driver behind the deterioration of air quality. Although $PM_{2.5}$ concentrations increased due to the recovery of activities after the post-COVID 19, the results signify the severity of pollution during the dry season of 2023, which peaked at 116 µg/m³, triggered by the intensity of El Niño. Through extreme rainfall reductions, El Niño significantly drives wider forest and land fires, as detected by the number and distribution of hotspots, which significantly influence particulate matter concentration (Maharani et al., 2021). The increasing PM2.5 levels were aligned with the decrease in rainfall, which acts to purify the air by washing away the suspended particulate matter (Mukhtar et al., 2013).

A comparison between the $PM_{2.5}$ levels during the day and night was also evaluated in more detail (**Figure 3**). The average $PM_{2.5}$ concentration at night (30.34 µg/m³) was generally higher than that during the day (25.95 µg/m³) for almost the entire year of 2023-2024. Both daytime and nighttime $PM_{2.5}$ levels peaked simultaneously in September–October 2023, with peak daytime and nighttime concentrations reaching 156.09 µg/m³ and 89.78 µg/m³, respectively. This pattern is consistent with common urban air pollution dynamics, which tend to decrease during the day (Qonita et al., 2025; Wang et al., 2015) and increase at night because of the stability of atmospheric conditions (Saxena & Naik, 2018; Zhao et al., 2009).

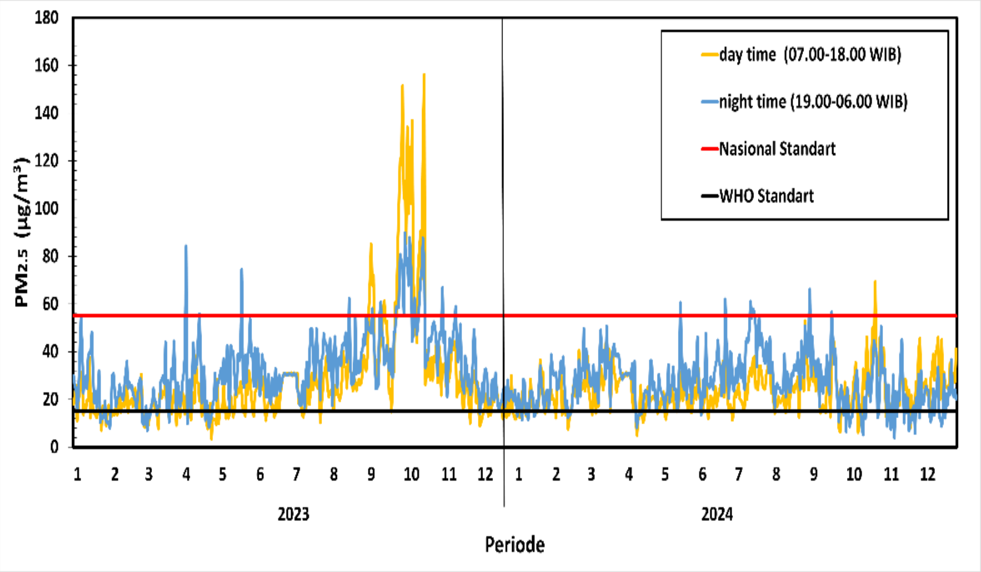

Figure 3. Daytime and nighttime levels of $PM_{2.5}$ concentrations in Jambi City during 2023-2024

The analysis also examined seasonal $PM_{2.5}$ variability to identify long-term trends, with an explicit comparison of pollutant levels during the dry, wet, and transition seasons (**Figure 4**). The rainy season showed the lowest and most stable $PM_{2.5}$ values compared to the other two seasons (the dry and transition seasons). These two seasons generally showed higher and more varied $PM_{2.5}$ concentration levels. The low $PM_{2.5}$ concentrations in the rainy season can be attributed to the rain-washing effect, where high rainfall effectively cleans pollutant particles in the atmosphere (Gusnita and Cholianawati, 2019). During the dry and transition seasons, drier conditions and minimal rainfall can increase forest and land fire activity in the Sumatra region, leading to higher $PM_{2.5}$ concentrations, as in Jambi Province. Similar situations were also found in Malaysia during 2018 – 2019 (Ma'amor et al., 2023) and in Pontianak City in 2023 (Qonita et al., 2025).

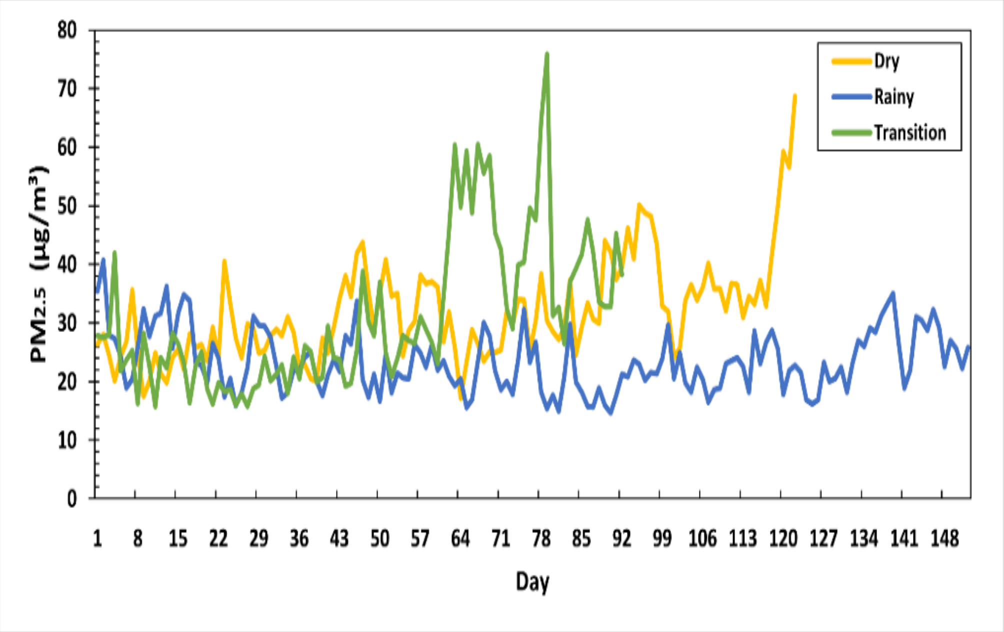

Figure 4. Seasonal comparison of $PM_{2.5}$ concentrations in Jambi City during 2023-2024

3.2. Meteorological influence on $PM_{2.5}$ concentrations

Figure S1 illustrates the influence of air temperature on $PM_{2.5}$ concentration in Jambi City, which generally exhibited a positive correlation in most seasons. Increased temperatures trigger photochemical reactions that form secondary particles and make dust particles lighter, allowing them to disperse and remain suspended longer in the atmosphere (Wang and Ogawa, 2015; Syafaati et al., 2023; Duppa et al., 2020). Humidity and rainfall played beneficial roles, acting as the atmosphere's "natural cleaners." During the rainy season, the atmosphere is in its most stable condition, where high humidity (above 80%) consistently correlates negatively with low $PM_{2.5}$ concentrations (**Figure S2**). Rainfall reinforces this effect, showing a negative correlation across all seasons through atmosphericscavenging orrthee "washout" process (**Figure S3**) (Kwak, et al., 2017). However, during the dry and transition seasons, when humidity and rainfall are minimal, the natural cleaning mechanism is weakened, particularly in the transition season. **Figure S4** shows that wind serves as an effective dispersal agent, exhibiting a negative correlation in which stronger winds spread pollutants and reduce local concentrations during the rainy season (Zhou, et al., 2020). Conversely, in the dry and transition seasons, wind shifts its role as a transportation agent. Higher wind speeds showed a positive correlation with $PM_{2.5}$, indicating that the wind carries pollutants from distant sources, such as smoke arriving in Jambi, thus replacing the dispersal effect (Wang and Ogawa, 2015).

Table 1 provides a quantitative interpretation of the meteorological influences on ambient $PM_{2.5}$. The regression analysis aimed to identify and measure the extent to which meteorological variables, that is, temperature, humidity, rainfall, and wind speed, influenced $PM_{2.5}$ concentration. The best contributions of the model were recorded during the transition (R^2 = 38.84 %) and rainy seasons (R^2 = 31.56 %). In the dry season, the role of weather drastically declines, with the model explaining only 21.77 % of the $PM_{2.5}$ variation. Humidity and rainfall, as air-cleansing factors, were almost always significantly influential across most analysis periods (2023-2024). However, humidity was non-significant in the rainy season, whereas rainfall was non-significant in the dry and transition seasons. Wind speed was significant in most seasons, but its role disappeared during the dry season. The low R^2 value, both for the overall period (2023-2024:24.10 %) and by season, strongly indicates that the main driver of $PM_{2.5}$ pollution in Jambi is not only meteorological factors. Emission sources such as forest and land fires and local human activities can also play a far more dominant role. This finding aligns with research in Bandung and Pontianak, where meteorological factors accounted for only a small portion of particulate variability (Turyanti, 2011; Qonita, et al., 2025).

Table 1. Regression results in the influence of meteorological factors to ambient $PM_{2.5}$

Period	**Parameters**	**Statistical Indicators**			
		P-Value	**R^2**	**Coefficients**	**Significance F**
2023-2024	Temperature	0.7472	0.2410	-0.2477	0.0000
	Humidity	0.0000		-1.4047	
	Rainfall	0.0003		-0.1410	
	Wind speed	0.0000		-1.6153	
2023	Temperature	0.9877	0.3377	0.0191	0.0000
	Humidity	0.0000		-2.0446	
	Rainfall	0.0374		-0.13086	
	Wind speed	0.0000		-2.3216	
2024	Temperature	0.0062	0.2271	1.9858	0.0000
	Humidity	0.0058		-0.3938	
	Rainfall	0.0003		-0.12299	
	Wind speed	0.0008		-1.0310	

Period	**Parameters**	**Statistical Indicators**			
		P-Value	**R^2**	**Coefficients**	**Significance F**
Rainy Season	Temperature	0.0000	0.3156	3.6824	0.0000
	Humidity	0.3279		0.1612	
	Rainfall	0.0010		-0.0944	
	Wind speed	0.0000		-1.2635	
Dry Season	Temperature	0.01560	0.2177	-3.6160	0.0000
	Humidity	0.0000		-1.4993	
	Rainfall	0.1107		-0.11753	
	Wind speed	0.7295		0.2712	
Transition Season	Temperature	0.0437	0.3884	-4.1573	0.0000
	Humidity	0.0000		-2.5485	
	Rainfall	0.0738		-0.2014	
	Wind speed	0.0185		2.8339	

3.3. Air mass trajectory analysis

Backward trajectory analysis provides insights into the origin of air masses associated with $PM_{2.5}$ episodes (Gusnita and Cholianawati, 2019). **Figure 5(a)–(c)** present the results for pollutants in Jambi City in the dry season on September 30, 2023, the wet season on November 13, 2023, and the transition period on October 18, 2023. These periods were selected because of the peak average of daily concentrations $PM_{2.5}$, representing the maximum or highest $PM_{2.5}$ concentration value during 2023-2024 in Jambi City. The results provide a clear understanding of how the direction of air mass movement affects $PM_{2.5}$ pollution concentration in Jambi City, particularly during the dry season (Muliane and Lestari, 2011). During the dry season (**Figure 5a**), $PM_{2.5}$ emission reached its highest point (peaking at 113.2 µg/m^3 on September 30, 2023), which were originated from the Southeast to the South (including South Sumatra, Lampung, and Bangka Belitung Island). This wind pattern, which is consistent with easterly monsoon winds, serves as the main pathway (Nieuwolt, 1977). This air trajectory crossed regions in Sumatra known for a very high number of hotspots. During the transition season from dry to wet (**Figure 5b**), which also frequently recorded extreme pollution (peaking at 116.2 µg/m^3 on October 18, 2023), the direction of air masses remained the same, moving from the Southeast to the South (South Sumatra and Lampung). However, $PM_{2.5}$ concentrations were significantly lower (peak concentration recorded at 50.7 µg/m^3 on November 13, 2023) in the rainy season, even though the trajectory still originated from the Southeast (South Sumatra and Bangka Belitung) (**Figure 5c**).

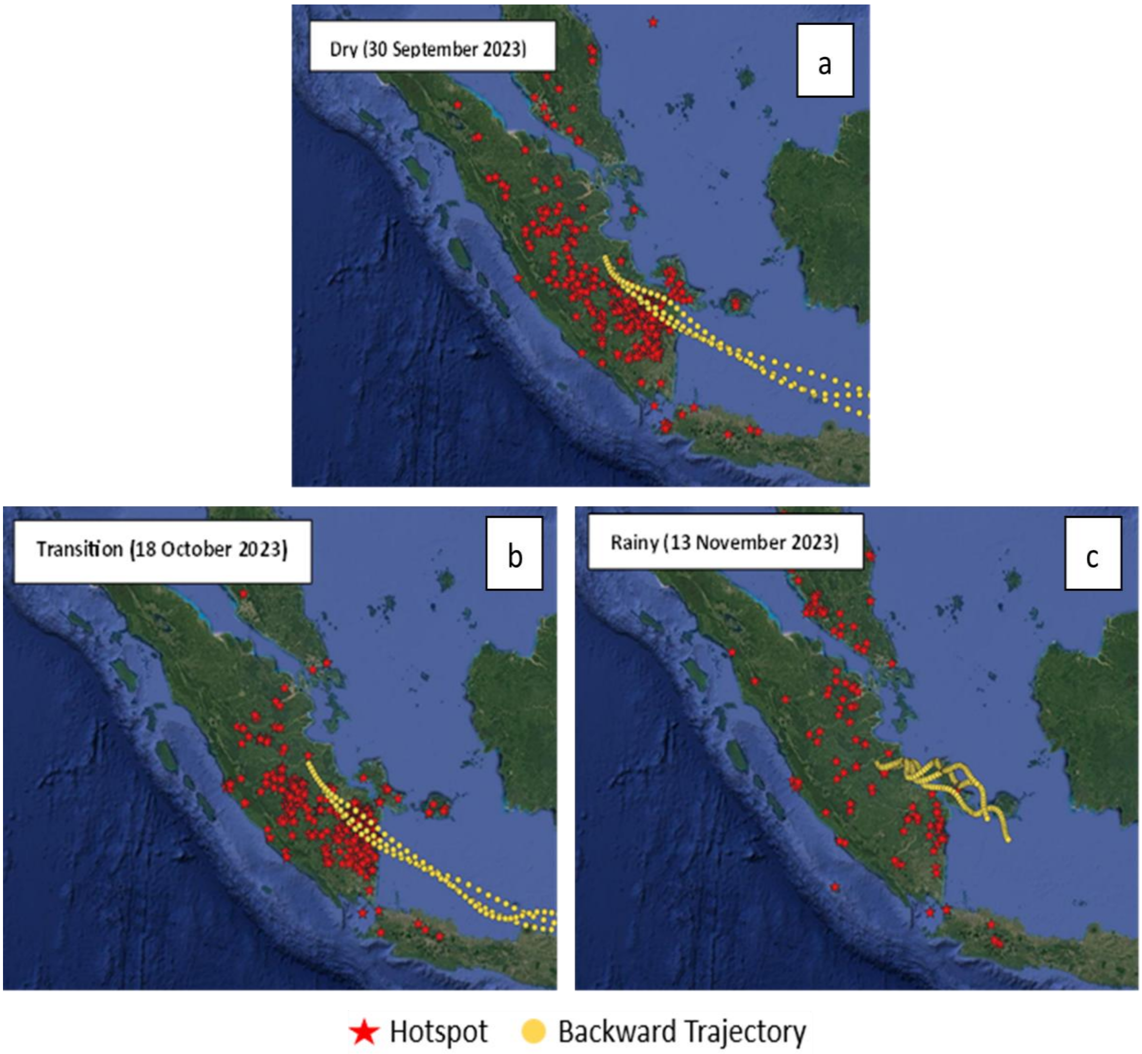

Figure 5. The air mass backward trajectories to Jambi City in each season of $PM_{2.5}$ maximum levels (a) dry; (b) transition; (c) rainy

3.4. Policy and Mitigation Insights

The results indicated that 3,69 % of the days in 2023-2024 exceeded the Indonesian daily standard, while 90,83 % of the days surpassed the WHO guideline. This affirms that the recovery of activities in the post-COVID-19 period has intensified the main pollution drivers from many sources. In this study, it was also found that regional forest and land fire activities became important again, while during the COVID-19 period, they dropped significantly. The importance of effective mitigation policies to protect both human health and the environment is crucial.

Mitigation efforts must also involve cooperation with other Sumatra regions, which are often major sources of fires during El Niño events. Collaborative regional monitoring with neighboring provinces is essential for effectively mitigating transboundary haze episodes. Moreover, local governments should strengthen early warning systems and integrate seasonal air quality forecasting into urban planning, especially during El Niño periods, to provide accurate and timely information to the public. This allows the community to take preventive measures to protect its health. Further studies should focus on chemistry-based source apportionment analysis to accurately separate the contribution of biomass from local vehicle and industrial emissions. Furthermore, integrating high-resolution pollution prediction models with long-term climate projections to predict haze risks will be important in the coming decades.

4. Conclusions

It can be concluded that the $PM_{2.5}$ concentrations in Jambi City are influenced by several factors. A very high spike in $PM_{2.5}$ occurred during the 2023 dry season, which was strongly correlated with forest and land fires in the Jambi region. However, 2024 showed much more stable $PM_{2.5}$ conditions owing to the absence of severe forest and land fires. Overall, the average $PM_{2.5}$ concentration has increased again in the Post-COVID-19 analysis (2023–2024) compared to the COVID-19 period (2020–2021). Meteorological factors also contributed, with temperature showing a positive correlation, where high temperatures can increase $PM_{2.5}$ through photochemical reactions, and wind speed can have both positive and negative correlations, acting as a dispersal agent or a long-range pollutant carrier. In contrast, humidity and rainfall consistently showed a negative correlation, where an increase in both effectively reduced $PM_{2.5}$ concentrations by washing pollutant particles from the atmosphere. However, they only explained a small portion of the $PM_{2.5}$ concentration variation, as indicated by the low R^2 values across all periods, particularly in the dry period. The air mass trajectories further confirmed that $PM_{2.5}$ has transboundary sources, which were shown while the maximum PM2.5 levels particularly originated from the Southeast-South direction (South Sumatra, Lampung, and Bangka Belitung Island). In the future, studies focusing on chemistry-based source apportionment are needed to accurately separate each contributed sources.

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Ethics Statement

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CRediT Author Statement

Benedy Fajar: Conceived and designed the analysis, collected data, contributed and analyzed tools, performed analysis, and wrote the paper. **Rizki Andre Handika**: Conceived and Designed Analysis, Contributed and Analysis Tools, Performed Analysis, Wrote Paper. **Muhammad Damris**: Conceived and Designed Analysis, Performed Analysis, Wrote Paper. **Kemas Rahmat Saleh Wiharja**: Contributed and Analysis Tools, Wrote Paper. **Elma Mutmainnah**: Conceived and Designed Analysis, Elma Mutmainnah, Wrote Paper. **Noorlin Mohammad**: Conceived and Designed Analysis, Wrote Paper.

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