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Analysis of PM Dispersion and Source Identification in Jl. Soekarno-Hatta, Pekanbaru, using HYSPLIT

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Abstract
This study investigates the spatiotemporal characteristics of PM pollution in Jl. Soekarno-Hatta, Pekanbaru, Indonesia, during January to November 2024, integrating air quality monitoring data, meteorological analysis, and HYSPLIT trajectory modeling. The highest PM concentration was recorded on 22–23 September 2024 at 55.74 µg/m³, corresponding to an AQI of 131, classified as "Unhealthy for Sensitive Groups." Monthly averages ranged from 18 µg/m³ in January to 56 µg/m³ in September. A total of 37 days exceeded 50 µg/m³, and 112 days surpassed the U.S. EPA's moderate threshold of 35 µg/m³. Meteorological data showed that low wind speeds (2.3–2.7 kph), persistent humidity (76–82%), and nighttime temperature inversions contributed to pollutant accumulation. Rainfall exhibited a strong inverse correlation with PM, with the driest month (June, 110 mm) aligning with high PM levels, and the wettest (November, 312 mm) aligning with lower concentrations (~21 µg/m³). HYSPLIT backward trajectory modeling revealed that air masses originated from the northwest, indicating contributions from transboundary sources such as peatland fires in West Sumatra. Forward trajectories showed that pollutants from Jl. Soekarno-Hatta, Pekanbaru, could reach Jambi and South Sumatra. The findings highlight the need for integrated air quality strategies, including emission reduction, fire prevention, and early warning systems, to mitigate PM exposure and protect vulnerable populations in tropical urban environments.
Keywords: *pekanbaru, pm, hysplit, wind*

Abstrak
Penelitian ini mengkaji karakteristik spasial dan temporal pencemaran PM di Pekanbaru, Indonesia, selama Januari hingga November 2024, dengan mengintegrasikan data pemantauan kualitas udara, analisis meteorologi, dan pemodelan trajektori HYSPLIT. Konsentrasi PM tertinggi tercatat pada 22–23 September 2024 sebesar 55,74 µg/m³, dengan AQI sebesar 131 dan diklasifikasikan sebagai "Tidak Sehat bagi Kelompok Sensitif." Rata-rata bulanan berkisar antara 18 µg/m³ pada Januari hingga 56 µg/m³ pada September. Sebanyak 37 hari tercatat melebihi 50 µg/m³, dan 112 hari melebihi ambang batas sedang versi U.S. EPA sebesar 35 µg/m³. Data meteorologi menunjukkan kecepatan angin rendah (2,3–2,7 kph), kelembapan tinggi (76–82%), dan inversi suhu malam hari berkontribusi terhadap akumulasi polutan. Curah hujan menunjukkan korelasi negatif kuat terhadap PM: bulan terkering (Juni, 110 mm) bertepatan dengan konsentrasi tinggi, sedangkan bulan terbasah (November, 312 mm) dengan konsentrasi lebih rendah (~21 µg/m³). Pemodelan trajektori mundur HYSPLIT menunjukkan massa udara berasal dari barat laut, mengindikasikan pengaruh sumber transboundary seperti kebakaran gambut di Sumatra Barat. Trajektori maju menunjukkan bahwa polutan dari Pekanbaru dapat mencapai Jambi dan Sumatera Selatan. Temuan ini menekankan perlunya strategi pengelolaan kualitas udara terpadu, termasuk pengendalian emisi, pencegahan kebakaran, dan sistem peringatan dini untuk melindungi populasi rentan di lingkungan perkotaan tropis.
Kata Kunci: *pekanbaru, pm, hysplit, angin*

1. Introduction

Throughout 2024, Jl. Soekarno-Hatta, Pekanbaru experienced significant fluctuations in particulate matter (PM) levels, primarily influenced by local meteorological conditions and regional pollutant sources. Extensive observations and predictive trends demonstrated clear seasonal variations in PM concentrations, governed by variables including ambient temperature, humidity, and wind circulation pattern [1-3]. Elevated PM levels often coincided with thermal inversion events, atmospheric phenomena characterized by a temperature increase with altitude, effectively restricting vertical air movement. This atmospheric stability results in pollutants becoming trapped near the ground, exacerbating air quality deterioration [4-

6]. Similar climatic conditions in comparable regions suggest that stagnant air during specific periods considerably amplifies pollution episodes, increasing the frequency and severity of such incidents.

Meteorological factors undeniably determine how PM disperses and accumulates within Jl. Soekarno-Hatta, Pekanbaru. Notably, wind velocity and prevailing wind direction critically affect the horizontal and vertical dispersion of airborne particles. Strong winds effectively disperse PM, diluting pollutant concentrations and mitigating air quality issues [7-9]. Conversely, weaker winds often correspond to stagnant air conditions, enabling PM to accumulate more readily and thus worsening local pollution levels [8]. Atmospheric stability caused by temperature gradients further complicates the dispersion patterns, often leading pollutants to concentrate in specific areas. Additionally, land-use changes and geographic characteristics contribute significantly to the development of localized microclimates. Such microclimates can intensify or alleviate pollution, depending on their unique spatial and topographical contexts [7, 10]

The application of the Hybrid Single-Particle Lagrangian Integrated Trajectory (HYSPLIT) model has become pivotal in identifying potential sources of PM impacting Jl. Soekarno-Hatta, Pekanbaru (Chang et al., 2021; Ilyas et al., 2022). Employing backward trajectory analysis allows researchers to effectively trace air mass movements reaching urban areas, providing valuable information regarding the origins and transport paths of airborne pollutants. Findings indicate that substantial portions of PM detected in Jl. Soekarno-Hatta, Pekanbaru originate externally, primarily linked to agricultural burning, industrial emissions, and vehicular exhaust from adjacent regions. Previous studies consistently show that locations downwind from major pollution sources experience heightened impacts, notably during dry periods characterized by increased biomass burning activities [11-13]. Seasonal agricultural activities and transboundary transport patterns significantly contribute to episodic spikes in PM concentrations, underlining the interconnectedness of regional pollution dynamics (Ahmad Mohtar et al., 2022; Pond et al., 2021; Wieser et al., 2021).

Despite the rising concerns over declining air quality in Jl. Soekarno-Hatta, Pekanbaru—intensified by recurring forest fires, heightened urban emissions, and complex meteorological interactions—comprehensive studies examining pollutant dispersion specifically within the urban landscape remain sparse. Limited localized research efforts have impeded the development of targeted, effective air quality management strategies. Recognizing this crucial knowledge gap, the current study seeks to provide a robust analytical framework for understanding PM dispersion within Jl. Soekarno-Hatta, Pekanbaru through a detailed data-driven methodology. This involves integrating real-time air quality measurements with HYSPLIT backward trajectory modeling [14, 15] to accurately depict pollutant movements and identify key source regions affecting the city throughout 2024.

By employing this systematic and detailed approach, the study anticipates uncovering significant insights regarding the mechanisms governing pollutant transport, accumulation, and dispersion. The identification and characterization of source regions and pathways are essential for developing informed mitigation strategies. Such targeted interventions are crucial for effectively managing air pollution, thus improving public health and environmental conditions in Jl. Soekarno-Hatta, Pekanbaru. Additionally, these insights can facilitate better preparedness and response measures during high-risk pollution periods, significantly enhancing urban resilience to adverse air quality events.

The combination of HYSPLIT modeling with empirical air quality data presents a comprehensive analysis, uniquely suited to addressing Jl. Soekarno-Hatta, Pekanbaru's specific environmental challenges. By closely examining how meteorological elements interact with regional and local emissions, the research provides a nuanced understanding of PM dynamics within the urban context. Furthermore, insights derived from this study could support policymakers and stakeholders in developing evidence-based decisions for urban planning and public health initiatives. Ultimately, the comprehensive analysis presented here aims to contribute substantially to the existing literature on urban air quality management, offering a detailed perspective on pollutant dispersion patterns, meteorological influences, and regional pollution transport dynamics specific to Jl. Soekarno-Hatta, Pekanbaru..

2. Material and Methods

2.1 Study Area

The research was carried out in Jl. Soekarno-Hatta, Pekanbaru City, the administrative capital of Riau Province, located on the island of Sumatra, Indonesia. Jl. Soekarno-Hatta, Pekanbaru is distinguished by a tropical climate, dense urban population, escalating vehicular traffic, and recurrent seasonal peatland fires, significantly contributing to airborne particulate matter (PM) concentrations. The monitoring location was centrally positioned at geographic coordinates of approximately 0.51°N and 101.44°E. Situated at an average elevation ranging from 13 to 16 meters above sea level, the city's predominantly flat topography notably impacts wind flow dynamics and subsequent pollutant dispersion.

2.2 Data Acquisition and Air Quality Index Transformation

The PM dataset utilized for this investigation was sourced from AQICN, which aggregates air quality data provided by local monitoring networks operated by agencies including the Meteorology, Climatology, and Geophysical Agency (BMKG) and the Environmental Agency. Data spanned from January to November 2024, encompassing daily Air Quality Index (AQI) values specific to Jl. Soekarno-Hatta, Pekanbaru. To obtain accurate PM concentration measurements (expressed in µg/m³), AQI values were transformed employing the US EPA breakpoint conversion method:

$$PM = \left(\frac{C_{hi}-C_{low}}{I_{hi}-I_{low}}\right) x \,(AQI - I_{low}) + C_{low}$$

Here, Clow and Chi signify the lower and upper boundaries of PM concentrations corresponding to AQI categories; Ilow and Ihigh represent the respective lower and upper AQI breakpoints; AQI denotes the daily Air Quality Index value. Monthly minimum and maximum PM concentrations were subsequently calculated, with the highest PM level recorded being 55.74 µg/m³ on 22–23 September 2024, indicating air quality categorized as "Unhealthy for Sensitive Groups."

2.3 HYSPLIT Trajectory Modeling

This study employed the HYSPLIT model, developed by NOAA, to simulate PM transport and dispersion [16, 17] within Jl. Soekarno-Hatta, Pekanbaru. Trajectory simulations included both forward and backward approaches to characterize pollutant dispersion patterns and identify potential source regions.

The backward trajectory simulations aimed to determine the origin of air masses transporting PM pollutants to Jl. Soekarno-Hatta, Pekanbaru. Simulations commenced at 08:00 UTC on 22 September 2024, coinciding with the recorded peak PM concentration. Simulations considered altitudes of 100 m, 500 m, and 1000 m above ground level over 48 hours. Lower altitude trajectories (100 m) indicated air mass origins from the southwest and west, implicating local or proximal regional emissions. In contrast, trajectories at higher altitudes (500–1000 m) extended toward northwest and northern regions, suggesting long-range transport of PM from areas such as West Sumatra, potentially linked to forest fires and regional biomass burning activities.

Forward trajectory simulations were similarly initiated to predict the dispersal paths of PM emanating from Jl. Soekarno-Hatta, Pekanbaru. Findings showed local dispersal primarily towards the southeast at the 100 m altitude, whereas PM at altitudes of 500 m and 1000 m traveled further eastward and northeastward, affecting regions beyond Riau Province such as Jambi and South Sumatra. Enhanced pollutant dispersion at elevated altitudes was indicative of stronger wind currents and greater vertical convective activity.

2.4 Dispersion Visualization Using HYSPLIT and Meteorological Parameters

Pollutant concentration gradients were visualized through the dispersion mode of the HYSPLIT model, incorporating meteorological data sourced from the Global Data Assimilation System (GDAS). Spatial PM concentration maps were generated across different altitudes, employing color-coded gradients to denote concentration intensities—red for highest concentrations ($>1.0 \times 10^{-12}$ mg/m³) and purple for lowest levels ($>3.2 \times 10^{-15}$ mg/m³). Notably, Jalan Bandeng and Tangkerang Tengah were identified as high PM concentration hotspots. Adjacent regions such as Kampung Tengah, Sail, and Sukajadi exhibited moderate exposure levels (orange and yellow zones), whereas peripheral localities like Kampung Melayu and Tangkerang Barat demonstrated lower PM concentrations, attributed to lower population density and increased vegetation coverage.

Meteorological conditions, notably wind speed, wind direction, temperature inversions, humidity, and atmospheric stability significantly influenced PM dispersion. Nighttime temperature inversions were identified as critical in trapping PM near the surface due to cooler air temperatures. Additionally, limited horizontal dispersion resulted from weak wind conditions at lower altitudes. Jl. Soekarno-Hatta, Pekanbaru's flat topography favored horizontal pollutant dispersal yet impeded vertical mixing. Dense urban development, heavy traffic emissions, and inadequate green infrastructure further exacerbated particulate accumulation. Peak AQI values reached 131, categorizing Jl. Soekarno-Hatta, Pekanbaru air quality as "Unhealthy for Sensitive Groups," as per US EPA and Indonesian government guidelines, prompting recommendations for preventive actions such as mask usage, activity restrictions, and air quality alerts by local authorities.

3. Results and Discussion

3.1 Temporal Variation of PM and Air Quality Index

During the study period from January to November 2024, Jl. Soekarno-Hatta, Pekanbaru exhibited substantial variability in daily particulate matter (PM) concentrations. Monthly mean PM levels fluctuated significantly, with the lowest average concentration observed in January at approximately 18 µg/m³, while the highest monthly average peaked at around 56 µg/m³ in September. Throughout this interval, PM concentrations frequently exceeded the WHO's recommended daily guideline of 25 µg/m³, particularly prevalent during the dry months spanning June through October. Notably, peak PM concentrations reached their highest on September 22–23, registering at 55.7 µg/m³, corresponding to an AQI value of 131, categorizing the air quality as "Unhealthy for Sensitive Groups."

Analyzing daily PM records, it was observed that approximately 37 days within the nine-month duration exhibited PM concentrations surpassing the critical threshold of 50 µg/m³. Additionally, PM values exceeding the U.S. EPA's moderate air quality benchmark of 35 µg/m³ were recorded for 112 days, indicating persistent air quality deterioration throughout the study period. These observations emphasize significant air pollution challenges in Jl. Soekarno-Hatta, Pekanbaru, notably during the late dry season, necessitating targeted intervention and mitigation strategies.

3.2 Meteorological Context in 2024

Meteorological conditions in Jl. Soekarno-Hatta, Pekanbaru in 2024 reflected the characteristics typical of tropical rainforest climates, with minimal temperature fluctuations throughout the year. Annual average temperatures ranged consistently between 26 and 27 °C, while monthly mean temperatures remained steady, showing minimal variation from average monthly highs of 32–33 °C to lows of 24–26 °C. High humidity levels persisted year-round, consistently recorded between 76–82%, with muggy conditions regularly approaching 100%.

Annual precipitation totaled approximately 2,500 mm, averaging about 209 mm monthly. The wettest month, November, received around 312 mm of rainfall, while June experienced the lowest rainfall, approximately 110 mm. Wind speeds across the year were low and exhibited limited variation, generally averaging between 2.3 and 2.7 kph. Wind direction shifted seasonally, predominantly originating from the south during May to October and from the north during November to March, influencing pollutant transport patterns.

3.3 Correlation Between PM and Meteorological Variables

A clear inverse correlation emerged between PM concentrations and rainfall. During periods of elevated precipitation, particularly notable in November (312 mm), PM concentrations averaged around 21 µg/m³, demonstrating the effectiveness of wet deposition in reducing particulate matter. Conversely, the dry season from June to October, with rainfall averaging between 110–160 mm, correlated with elevated PM concentrations ranging from 35–56 µg/m³. Specifically, in September, when rainfall was recorded at approximately 125 mm, PM levels peaked, reinforcing the established negative correlation. The linear regression analysis produced a determination coefficient (R^2) of approximately 0.64, indicating significant inverse dependence of PM concentrations on rainfall amounts.

Wind conditions, characterized predominantly by low velocities averaging around 2.5 kph, significantly restricted the dispersion of pollutants, especially in lower atmospheric layers. From June to October, weak winds, combined with dry environmental conditions, facilitated local stagnation and the consequent accumulation of PM. Southern winds during May–October likely introduced pollutants originating from southern peatlands and urban traffic emissions, exacerbating local air quality. Post-November, the northerly winds potentially aided in diluting pollutants by transporting cleaner air from wetter northern zones.

A modest negative correlation ($R \approx -0.43$) between wind speed and PM concentrations indicated that stronger winds facilitated pollutant dispersion, temporarily reducing PM levels by approximately 10–15 µg/m³ during episodes of wind gusts exceeding 5 kph. Furthermore, elevated temperatures around 33 °C exhibited a weak correlation with increased PM concentrations, particularly under conditions of thermal inversion prevalent during dry spells. Nighttime inversion conditions coupled with high humidity trapped pollutants close to the ground, with peak PM concentrations typically recorded between 4–8 AM local time, aligning with standard atmospheric boundary-layer behaviors.

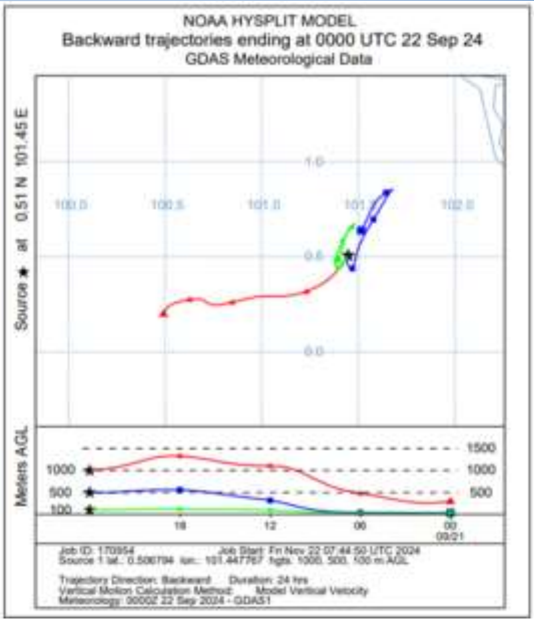

Fig 1. Using HYSPLIT to identify wind direction around central Jl. Soekarno-Hatta, Pekanbaru

3.4 HYSPLIT Trajectory Analysis

Employing the HYSPLIT model, backward trajectory simulations initiated on 22 September at altitudes of 100 m, 500 m, and 1000 m provided insights into pollutant origin. Results showed localized emission sources predominantly influencing lower altitude air masses (100 m), primarily within central urban corridors in Jl. Soekarno-Hatta, Pekanbaru. Conversely, trajectories at higher altitudes (500–1000 m) traced air masses originating from northwest regions such as West Sumatra, indicating transboundary pollutant transport associated with regional forest fires and biomass burning activities. Forward trajectory simulations demonstrated localized dispersion patterns at lower altitudes, predominantly affecting areas within approximately 50 km of the central urban region. However, dispersion at higher altitudes extended pollutants significantly southeastward and northeastward, potentially impacting regions beyond Riau Province, including Jambi and South Sumatra within 48 hours. This highlights the implications of regional atmospheric dynamics on air quality in adjacent provinces.

Spatial dispersion maps generated using HYSPLIT's GDAS-driven concentration gradients identified Jalan Bandeng and Tangkerang Tengah as notable PM hotspots, correlating strongly with high-density urbanization and intensive vehicular traffic. Moderate PM exposure zones included Kampung Tengah, Sail, and Sukajadi, while peripheral areas such as Kampung Melayu and Tangkerang Barat exhibited reduced pollutant concentrations, benefiting from lower population density and greater vegetation coverage. Overall, findings from 2024 align well with previous research in Southeast Asia, highlighting persistent seasonal haze issues exacerbated by regional biomass burning. Jl. Soekarno-Hatta, Pekanbaru's PM baseline (approximately 30 μg/m³) surpassed neighboring urban areas, likely due to intensified traffic emissions and industrial activities. The study underscores the critical role of meteorological factors—precipitation as a cleansing agent, and wind stagnation and temperature inversions facilitating pollutant accumulation.

While the study relied heavily on a single monitoring station, future research recommendations include establishing denser sensor networks and integrating aerosol lidar observations to accurately distinguish between local and transboundary pollution sources. Enhanced statistical methodologies, such as multiple regression analyses involving PM, wind speed, rainfall, and humidity, could provide additional quantitative validation. Long-term monitoring would further clarify impacts related to climate anomalies, including ENSO or MJO phases.

4. Conclusion

This study analyzed PM pollution dynamics in Jl. Soekarno-Hatta, Pekanbaru from January to November 2024, integrating air quality data, meteorological analyses, and HYSPLIT modeling. PM concentrations exhibited distinct seasonal variations, peaking notably in September with the highest concentration recorded at 55.74 μg/m³ (AQI of 131), categorized as "Unhealthy for Sensitive Groups." This condition represents significant health risks, particularly for vulnerable groups. Meteorological variables—including low wind speeds, high humidity, and nighttime temperature inversions—strongly influenced pollutant accumulation. Rainfall demonstrated an inverse relationship with PM concentrations, confirming the effectiveness of wet deposition in particulate reduction. HYSPLIT trajectory analyses indicated both local and transboundary pollution sources, highlighting contributions from regional biomass burning in adjacent provinces. The results emphasize the necessity for integrated air quality management, enhanced regional cooperation, proactive fire control measures, and continuous public health alerts to effectively address air pollution and protect public health in Jl. Soekarno-Hatta, Pekanbaru.

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