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Spatial Analysis of $PM_{2.5}$ Data from Low-Cost Sensor Related to Economic Activities in Pekanbaru City

Retno Tri Wahyuni[1*], Juni Nurma Sari[2], Kartina Diah Kesuma Wardhani[2], Tobi Arfan[3], Dadang Syarif Sihabudin Sahid[2], Siti Afiqah Zainuddin[4,5]

[1] Industrial Technology Department, Politeknik Caltex Riau, Pekanbaru 28265, Indonesia
[2] Information Technology Department, Politeknik Caltex Riau, Pekanbaru 28265, Indonesia
[3] Tax and Accounting Department, Politeknik Caltex Riau, Pekanbaru 28265, Indonesia
[4] Faculty of Entrepreneurship and Business, Universiti Malaysia Kelantan, Kelantan 16100, Malaysia
[5] Department of Accounting, Economics and Finance, School of Business Administration, European University Cyprus, Egkomi 2404, Cyprus

Corresponding Author Email: retnotri@pcr.ac.id

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ABSTRACT

Pekanbaru, a major economic hub in Sumatra, faces air quality challenges due to rapid urbanization and economic growth. $PM_{2.5}$ pollution, driven by economic activities and recurring forest fires, poses significant health risks. While Indonesia's Air Pollutant Standard Index (ISPU) provides a regulatory framework, traditional air quality monitoring is limited by high costs, encouraging the use of low-cost portable sensors. This study utilizes such sensors to collect $PM_{2.5}$ data from 18 locations over three days. Spatial analysis reveals stable $PM_{2.5}$ patterns influenced by daily economic activities, with most areas classified as "Moderate," though some exhibit higher concentrations requiring attention. Spearman correlation analysis highlights strong links between $PM_{2.5}$ levels and residential areas (r=0.75), farmland (r=0.73), healthcare centers (r=0.73), hotels (r=0.7), and commercial centers (r=0.64). Transportation also significantly impacts $PM_{2.5}$, indicated by road length (r=0.65). In contrast, negative correlations with plantation areas (r=−0.63) emphasize the role of green spaces in mitigating pollution. Industrial areas (r=0.12) and terminals (r=0.33) have minimal influence, reflecting their localized nature. To reduce $PM_{2.5}$ pollution, Pekanbaru should expand green spaces, regulate biomass burning, promote eco-friendly transport, and adopt balanced land-use planning. Public education is crucial to enhance air quality and protect public health.

1. INTRODUCTION

Pekanbaru, the capital city of Riau Province, spans an area of 632.26 km² and serves as the largest economic hub in eastern Sumatra. Over the past decades, Pekanbaru has experienced rapid growth, particularly in the industrial and trade sectors, solidifying its role as a center of economic activity in the region. However, this growth poses significant challenges to environmental sustainability, particularly in maintaining air quality. Among the various pollutants, Particulate Matter 2.5 ($PM_{2.5}$) is a critical concern due to its ability to penetrate the respiratory system and bloodstream, leading to severe health impacts, including increased mortality rates [1-3].

In Pekanbaru, $PM_{2.5}$ emissions originate from a combination of human activities, such as transportation, industrial processes, and recurring forest fires in the surrounding Riau Province. Studies indicate that Pekanbaru consistently records the highest annual average $PM_{2.5}$ concentration outside Java Island [4]. This aligns with the city's rapid urbanization, rising population, and economic activities, including the increased use of motor vehicles and coal combustion, all of which significantly contribute to pollution levels.

The rapid economic growth in Pekanbaru significantly impacts air quality, including $PM_{2.5}$ concentrations. Previous studies in China have shown a one-way causality between $PM_{2.5}$ and economic growth, indicating that increased economic activity directly affects air quality [5]. Traffic congestion resulting from economic growth and urbanization has become a major source of pollutants in the transportation sector. Literature reviews by other researchers highlight various relationships between traffic-related variables and air quality in air quality modeling [6]. Additionally, resource processing industries also contribute to increased air pollutants.

Despite regulatory frameworks such as Indonesia's Air Pollutant Standard Index (ISPU), as stipulated in the Ministry of Environment and Forestry Regulation No. 14 of 2020, air quality monitoring efforts in Indonesia are often limited by the high costs of investment and operation associated with traditional air quality monitoring stations. To address this limitation, low-cost portable sensors have emerged as a flexible and economical alternative, enabling the collection of spatially specific air quality data [7-10]. These portable sensors can be positioned at several representative points, providing an overview of air quality conditions within a narrower and more specific space. These sensors, often integrated with IoT technology, allow for continuous data collection and transmission, offering a more detailed and localized understanding of air quality conditions.

Spatial modeling has further enhanced the ability to visualize and analyze air pollution in specific urban spaces, leveraging data from multiple representative sampling points [8, 11]. This approach not only provides actionable insights into localized pollution sources but also facilitates correlation analyses between air quality and urban factors, such as economic activities.

This study aims to spatially analyze $PM_{2.5}$ data collected using a portable spatial data logger in Pekanbaru. By correlating $PM_{2.5}$ data with economic activity variables, this research explores the intricate relationship between air pollution and the city's economic development. While similar studies have been conducted in other countries, there is a notable lack of research focusing on Pekanbaru. The findings of this study are expected to provide valuable insights for air quality management and inform sustainable urban planning in rapidly developing cities like Pekanbaru.

2. STUDY AREA

Pekanbaru City, the capital of Riau Province, covers an area of 632.26 km². Geographically, it is located between 101°14'–101°34' East Longitude and 0°25'–0°45' North Latitude. Figure 1 illustrates Pekanbaru based on Pekanbaru City Regional Regulation No. 2 of 2020, the city is divided into 15 districts: Payung Sekaki, Tuah Madani, Bina Widya, Bukit Raya, Marpoyan Damai, Tenayan Raya, Kulim, Limapuluh, Sail, Pekanbaru Kota, Sukajadi, Senapelan, Rumbai, Rumbai Barat, and Rumbai Timur.

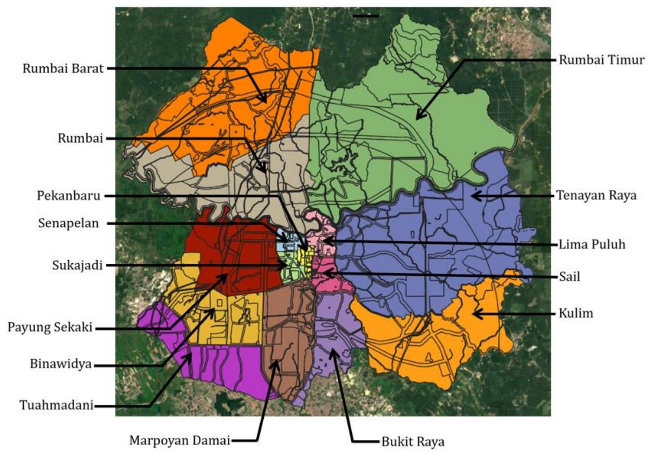

Figure 1. Pekanbaru City regional

Pekanbaru, as the largest economic hub in eastern Sumatra, has witnessed rapid urbanization and industrial growth [12, 13], resulting in increasing air quality challenges. Its 15 districts present a diverse mix of economic activities, residential areas, and infrastructure, which makes it an ideal study area for analyzing the relationship between $PM_{2.5}$ concentrations and economic activities.

3. MATERIAL AND METHOD

The overview of the research framework is presented in Figure 2. In order to identify the regions for data collection, the study framework starts with spatial sampling methods. $PM_{2.5}$ data collection and economic activities data collection are the two primary parts of the process. To acquire $PM_{2.5}$ data, a low-cost data logger is created and used to measure $PM_{2.5}$ concentrations. Temporal sampling methods are then used to collect data during predetermined time periods. Concurrently, the gathering of data on economic activities concentrates on land use classification and calculating the number of each land use variable to reflect the economic activity of the research region.

Two correlation strategies are then used in the spatial analysis methods used to examine the gathered data. First, the linear link between $PM_{2.5}$ concentrations and economic activity is evaluated by Pearson correlation, whereas the monotonic relationship is evaluated by Spearman correlation.

Strategies for mitigation and pollution control are developed using the findings from the geographical analysis and correlation approaches. This last phase focuses on determining and putting into practice spatial methods to lower $PM_{2.5}$ pollution while taking economic activity and land use patterns into account. All things considered, this framework offers a methodical way to comprehend the connection between land use and air pollution, finally directing efficient pollution control measures.

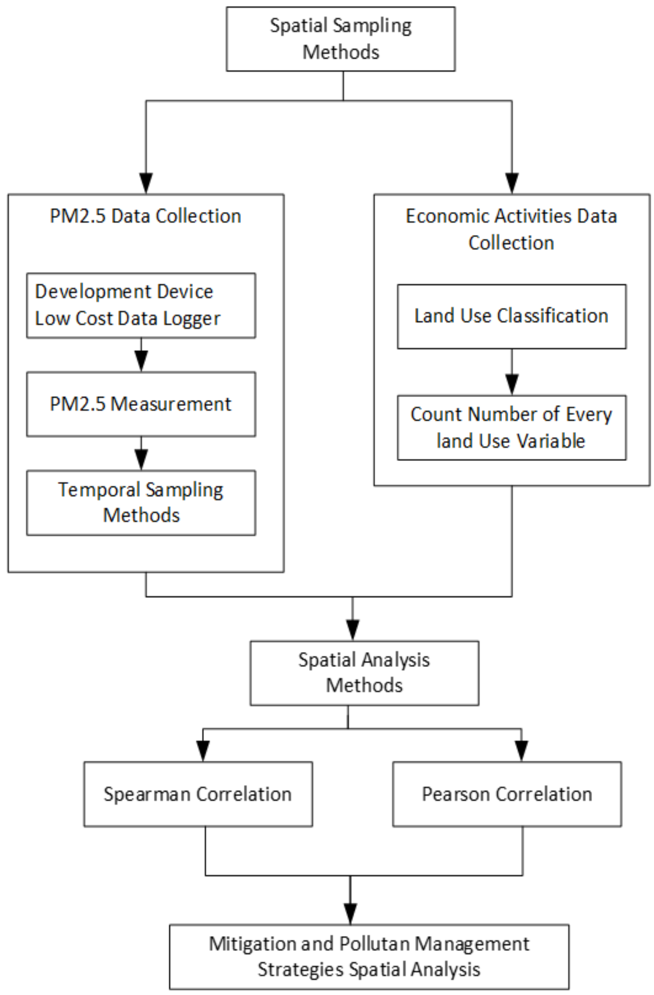

Figure 2. Research framework

3.1 $PM_{2.5}$ data collection

In this study, $PM_{2.5}$ data were collected using a device equipped with a low-cost sensor. The data collection process was carried out through a sampling method at multiple representative points across Pekanbaru City.

3.1.1 Device

The device used in this study is a spatial data logger, designed to record $PM_{2.5}$ data along with the time and location of the device's operation. The device stores its operational coordinates in the form of latitude and longitude points. The main components of the spatial data logger include a $PM_{2.5}$ sensor, a microcontroller, a microSD card, and a GPS (Global Positioning System) module. In addition, the device is equipped with weather sensors, including temperature, humidity, air pressure, and light intensity sensors. These meteorological parameters function to verify environmental conditions during data collection, ensuring that weather conditions remain homogeneous throughout the sampling process. By monitoring parameters such as temperature, humidity, air pressure, and light intensity, the device ensures consistency in environmental conditions during the sampling period. However, while these weather data were collected, this paper does not present or analyze them in detail. Future studies should consider incorporating a more thorough analysis of how these meteorological factors influenced the observed $PM_{2.5}$ concentrations. Such an analysis could provide a deeper understanding of the factors affecting air quality, strengthening the interpretation of the results. The structure of the spatial data logger device is depicted in Figure 3.

Figure 3. Spatial data logger

3.1.2 Spatial sampling method

The selection of $PM_{2.5}$ observation points in this study was based on the grid method, which involves dividing the study area into smaller, manageable regions. The grid resolution used by previous researchers has varied significantly, ranging from 500 meters [14], suitable for high-resolution urban studies, to 10 kilometers [15], often applied for regional or large-scale assessments. Smaller grid sizes allow for more detailed spatial analysis but require increased resources, while larger grid sizes may oversimplify spatial variations.

In this study, a grid resolution of 5 km was chosen as an intermediate scale to strike a balance between achieving sufficient spatial accuracy and maintaining resource efficiency. This resolution was deemed appropriate based on studies [16], which demonstrated that a 5 km spatial resolution is effective for spatial analysis as it produces $PM_{2.5}$ estimates that meet national air quality standards. This is supported by $PM_{2.5}$ estimation models based on AOD in the Yangtze River Delta (YRD), which showed strong performance at resolutions of 1, 3, and 5 km compared to the coarser 10 km resolution. Another study by Aleksankina et al. [17], utilizing the EMEP4UK model, also indicated that a 5 km × 5 km spatial resolution is reliable for spatial analysis of air pollutants, including $PM_{2.5}$. This resolution allows for a more detailed representation of surface concentrations in urban areas while maintaining computational efficiency through an emulator-based approach.

The process of dividing Pekanbaru City into grids was performed using QGIS software, resulting in a total of 34 grid cells. To optimize resources while maintaining the representativeness of the spatial variability of $PM_{2.5}$, the observation points were reduced from 34 to 18. Each point was strategically selected to capture varying land use characteristics across the city, ensuring that residential, industrial, commercial, and other relevant zones were represented. Figure 4 illustrates the distribution of observation points, where most grids have one sample point, except for one grid with two points (17 and 18). This grid was assigned additional points due to its central location, high emission sources, and dense urban activity, which warranted more detailed monitoring.

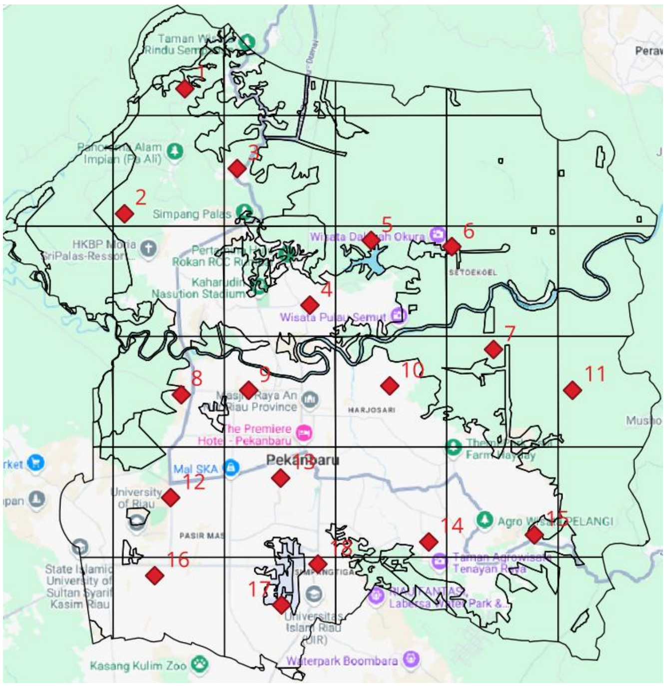

Figure 4. The $PM_{2.5}$ sampling map

The geographical and administrative locations of each sample point are detailed in Table 1, including their exact coordinates (latitude and longitude) and corresponding districts in Pekanbaru City. This table highlights the spatial distribution of observation points, providing a basis for understanding the relationship between $PM_{2.5}$ concentrations, land use patterns, and urban activities.

3.1.3 Temporal sampling method

For the temporal aspect of data collection, $PM_{2.5}$ measurements were conducted during the diurnal period, spanning from 8:00 AM to 5:00 PM, over three consecutive days. This time frame was selected to capture the variations in air quality throughout a typical day, aiming to reflect the general pattern of $PM_{2.5}$ concentrations in the study area. The data collection occurred between August and September 2024, a period free from forest fire events in Riau Province and its surrounding regions. While this three-day period provides a snapshot of air quality conditions in the study area, it is important to acknowledge that it may not fully capture potential seasonal variations in $PM_{2.5}$ concentrations. Seasonal factors, such as changes in meteorological conditions and regional activities, could influence air quality patterns over a longer time frame. Future studies should consider extended data collection across different seasons to provide a more comprehensive understanding of $PM_{2.5}$ trends in Pekanbaru. Despite this limitation, the selected period without forest fire events offers an opportunity to analyze $PM_{2.5}$ levels under relatively stable environmental conditions. The $PM_{2.5}$ concentration trends observed over the three-day period were analyzed to identify temporal patterns and correlations with specific times of the day. This ensures that the collected data accurately represents the typical air quality conditions at each sampling location. Additionally, daily average $PM_{2.5}$ concentrations for the diurnal period were calculated and subsequently used in spatial analysis. These averages serve as a representative indicator of the prevailing air quality conditions for each sampling point, supporting the robustness of the spatial modeling.

Table 1. Sampling point location

Point	Lattitude	Longitude	District
1	0.658523	101.4001	Muara Fajar, Rumbai Barat
2	0.607523	101.3756	Rumbai Bukit, Rumbai Barat
3	0.62574	101.4213	Muara Fajar, Rumbai Barat
4	0.56993	101.4508	Lembah Sari, Rumbai Timur
5	0.596325	101.4756	Lembah Damai, Rumbai
6	0.593742	101.5085	Tebing Tinggi Okura, Rumbai Timur
7	0.551818	101.5252	Bencah Lesung, Tenayan Raya
8	0.533671	101.3985	Air Hitam, Payung Sekaki
9	0.535228	101.4259	Tampan, Payung Sekaki
10	0.536982	101.4831	Rejosari, Tenayan Raya
11	0.535439	101.5573	Bencah Lesung, Tenayan Raya
12	0.491436	101.3945	Simpang Baru, Binawidya
13	0.49961	101.4389	Tangkerang, Bukit Raya
14	0.473543	101.4989	Tangkerang, Bukit Raya
15	0.476352	101.5417	Kulim, Kulim
16	0.459713	101.388	Tuah Karya, Tuahmadani
17	0.447659	101.4394	Perhentian Marpoyan, Marpoyan Damai
18	0.464458	101.4541	Simpang Tiga, Bukit Raya

3.2 Economic activities data collection

Economic activity encompasses all actions related to producing, distributing, or consuming goods and services within a specific geographic area. For this research, economic activity is categorized based on land-use classifications, which include Agricultural, Industrial and Economic Activities, Public Services and Institutions, Transportation and Infrastructure, and Residential and Living Areas.

Each zone is analyzed for the intensity and type of economic activities, including agriculture, industry, commerce, public services, infrastructure, and residential density. The collected data is then spatially linked to the corresponding $PM_{2.5}$ measurement points, enabling an analysis of how economic activity distribution correlates with air quality in Pekanbaru.

To determine the boundaries and extent of each land-use category, land-use maps of Pekanbaru City and online tools like Google Maps were used. The area and count of each land-use category were then calculated using Geographic Information System (GIS) software, specifically QGIS, to ensure accurate spatial analysis and facilitate the integration of economic activity data with $PM_{2.5}$ measurements.

3.3 Spatial analysis method

The spatial analysis in this study aimed to investigate the relationship between $PM_{2.5}$ concentrations and economic activities in Pekanbaru City using cross-correlation analysis. $PM_{2.5}$ data from low-cost sensors at 18 sampling points were spatially referenced and linked to land-use categories representing economic activities. The data were aggregated to represent daily average concentrations during the diurnal period at each point and then correlated with the economic activity characteristics of each zone.

The analysis process was carried out by calculating cross-correlation values using both Pearson and Spearman methods. Pearson correlation is used to measure the linear relationship between two variables, while Spearman correlation assesses monotonic relationships, regardless of linearity. These methods have been commonly applied in similar studies [18, 19]. By analyzing the cross-correlation between $PM_{2.5}$ and economic activity variables, factors influencing the spatial variability of $PM_{2.5}$ can be identified.

The Pearson correlation coefficient ranges from -1 to 1. A value of zero indicates no correlation, a positive value indicates a positive correlation and a negative value indicates a negative correlation. Furthermore, higher absolute values indicate stronger correlations. The Pearson correlation coefficient was calculated using Eq. (1) to analyze the contribution of various pollutants to $PM_{2.5}$ [19, 20]. In this equation, x_i and y_i represent the data points to be correlated, while $\bar{x}$ and $\bar{y}$ are the mean values of each dataset.

$$r = \frac{\sum_{i=1}^{n}(x_i - \bar{x}) - (y_i - \bar{y})}{\sqrt{\sum_{i=1}^{n}(x_i - \bar{x})^2 \sum_{i=1}^{n}(y_i - \bar{y})^2}} \tag{1}$$

Like the Pearson correlation, the Spearman correlation coefficient also ranges from -1 to 1. The main difference between Spearman and Pearson correlation lies in the use of ranked data in its calculation [21, 22] making it more robust to outliers and variability in data, as well as suitable for non-linear relationships. The Spearman correlation was calculated using Eq. (2) [18]. In this equation, d_i represents the difference between the ranks of two variables for each observation, while n is the number of observations.

$$r = 1 - \frac{6\sum_{i=1}^{n} d_i}{n(n^2 - 1)} \tag{2}$$

In addition to analyzing the cross-correlation between $PM_{2.5}$ concentrations and land use, cross-correlation analysis was also conducted among different land-use variables. This step was essential to explore potential interactions or overlapping effects between various types of economic activities, such as the interplay between industrial zones and transportation infrastructure or the influence of residential density on public service zones. Understanding these interactions provides a more nuanced perspective on how combined land-use patterns may contribute to variations in air quality.

This comprehensive approach enabled the identification of critical zones and factors where economic activities and their interactions significantly impact $PM_{2.5}$ concentrations. Insights gained from this analysis are expected to support spatial planning strategies by highlighting areas for targeted interventions, contributing to more sustainable urban and regional development in Pekanbaru City.

4. RESULT AND DISCUSSION

4.1 $PM_{2.5}$ concentration trends

The results of data collection over three consecutive days at 18 sample points in Pekanbaru City reveal a consistent and clear pattern in the distribution of $PM_{2.5}$ concentrations. These results show fluctuations in $PM_{2.5}$ levels that follow the expected diurnal trend, with concentrations varying throughout the day due to factors such as traffic, industrial activity, and meteorological conditions. The observed $PM_{2.5}$ concentrations reflect typical urban air quality variations, with higher levels usually occurring during peak traffic hours and in areas with more intense industrial or commercial activity.

To ensure the reliability of the data, the consistency of $PM_{2.5}$ concentrations across the measurement points was tested by calculating the standard deviation ratio. The results showed that the data for each measurement point is fairly consistent, with the criteria 20% ≤ standard deviation ratio ≤ 40%. This indicates that the data collected is stable and reliable, and therefore, the sample data at all points can be considered a valid representation of the daily average $PM_{2.5}$ concentration for those locations. This consistency is crucial for further spatial analysis.

Figure 5 presents a box plot of the measurement data collected over three days at each measurement point. This box plot effectively illustrates the variability of $PM_{2.5}$ concentrations across different sample points, highlighting the range and distribution of values over the measurement period. The box plot also identifies potential outliers, offering a detailed view of the data spread and further strengthening the reliability of the overall dataset.

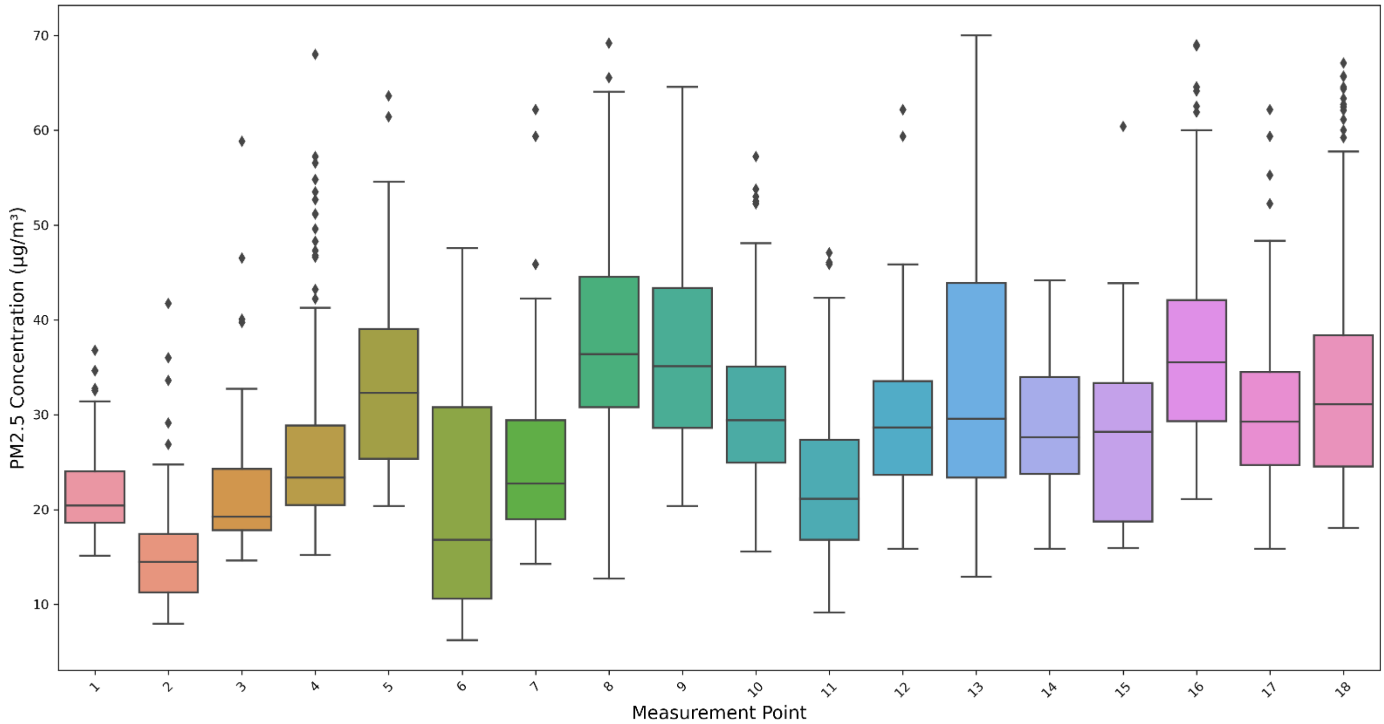

Figure 5. The box plot of $PM_{2.5}$ concentration at 18 measurement points

Subsequently, the average $PM_{2.5}$ concentration values for each measurement point were calculated and presented in Table 2. These averages, derived from the three-day data collection period, provide a solid foundation for analyzing the spatial distribution of $PM_{2.5}$ concentrations in Pekanbaru and their relationship to economic activities.

4.2 $PM_{2.5}$ concentration trends

Economic activities in a region can be identified through the land use in that area. In this study, land use is divided into several variables, namely Agricultural (Plantation and Farm), Industrial and Economic Activities Infrastructure (Industry, Commercial Center, Hotel, Terminal, Road Length), Public Services and Residential Areas (Healthcare Center, Government Building, Educational Building, Residential).

The selection of variables to identify economic conditions is based on the consideration that Pekanbaru is an urban area with trade as its main economic sector. Pekanbaru is well-known as an exhibition city and a trade center in the Sumatra region, with various economic activities related to manufacturing industries, trade, and the service sector. The presence of markets, shopping centers, and industrial areas serves as key indicators in portraying the city's economic dynamics. Additionally, economic activities in the transportation sector, such as terminals and highways, also play a significant role in supporting the movement of goods and people, which sustains the local economy.

Table 2. Average $PM_{2.5}$ data at sampling points

Point	Average (µg/m³)
1	22
2	15
3	21
4	27
5	33
6	20
7	30
8	40
9	38
10	32
11	24
12	33
13	53
14	29
15	27
16	43
17	33
18	38

4.2.1 Agriculture activities

The results of land use identification and surveys using Google Maps provided data for each variable on the grid represented by measurement sample points, as presented in Tables 3 to 5.

Table 3. Plantation and farm area

Point	Plantation (km²)	Farm (km²)
1	9.59	0
2	21.54	0
3	17.44	0
4	6.73	3.11
5	15.52	2.26
6	19.78	0
7	24.75	0
8	16.81	2.17
9	2.12	2.97
10	12.53	5.79
11	19.38	0
12	11.72	8.03
13	0.75	9.57
14	6.72	9.77
15	21.74	0.26
16	1.08	10.82
17	0.31	8.66
18	0.31	8.66

The data in Table 3 illustrates the distribution of plantation and farmland areas across various measurement points in the Pekanbaru City region. The point with the largest plantation area is located in the southern part of Pekanbaru, represented by Point 7, followed by Points 2 and 6, which are situated in the northern region. Meanwhile, several areas in the western and southern parts of Pekanbaru, represented by Points 13, 16, 17, and 18, show a greater contribution of farmland compared to plantations.

Some points exhibit a combination of plantation and farmland, such as Points 4, 5, and 8, each with a diverse proportion of plantation and farmland, though no point is entirely dominated by farmland. On the other hand, points 1, 2, 3, 6, and 7 consist solely of plantation areas with no farmland, potentially reflecting regions more focused on large-scale plantation activities.

Overall, this data depicts a varied distribution of agricultural activities, with some points dominated by plantations, while others show a mix of plantations and farmlands. This distribution pattern may reflect differences in land use based on the dominant type of economic activity in each region, which could influence policies related to natural resource management and land use planning in the area.

4.2.2 Industrial and economic activities infrastructure

Furthermore, Table 4 presents the land use conditions in Pekanbaru for Industrial and Economic Activities Infrastructure, including the number of industrial buildings, commercial centers, hotels, terminals, and road length. Essentially, Pekanbaru is a trade-oriented city, with relatively few processing industries operating within its area. However, there are some manufacturing industries and one power plant.

As a major city and commercial hub, Pekanbaru serves as a destination for people from surrounding areas. Supporting facilities such as hotels are crucial to facilitate visitors' economic activities, as well as terminals and roads as transportation routes. For this reason, the number of hotels, commercial centers, terminals, and road length have been analyzed as parameters in this study.

Table 4. Industrial and economic activities infrastructure

Point	Industry (unit)	Commercial Center (unit)	Hotel (unit)	Terminal (unit)	Road Length (km)
1	0	0	0	0	32.76
2	0	0	0	0	58.77
3	0	0	0	0	80.82
4	2	1	0	2	145.17
5	0	0	0	1	74.99
6	1	0	0	0	55.28
7	1	0	0	0	109.15
8	4	1	0	0	93.43
9	11	18	26	1	217.90
10	2	2	1	0	104.29
11	0	0	0	0	151.05
12	0	3	3	4	172.81
13	0	8	22	3	234.91
14	0	3	0	1	182.50
15	0	2	0	0	127.22
16	0	2	1	0	172.76
17	0	1	1	0	171.25
18	0	1	1	0	171.25

Based on the data presented in Table 4, there is a distribution of facilities such as industrial buildings, commercial centers, hotels, terminals, and road lengths across various measurement points. Point 9, located in Payung Sekaki District, stands out with the highest concentration of these facilities, including 11 industrial units, 18 commercial centers, 26 hotels, and a road length of 217.90 km. This indicates that Point 9 is likely a central area for economic and transportation activities.

Conversely, points such as points 1, 2, and 3 in Rumbai Barat District lack industrial, commercial, hotel, or terminal facilities, although they still feature significant road lengths, possibly reflecting transitional areas or regions predominantly used for transportation.

An interesting pattern emerges, showing a relationship between road length and the number of facilities, particularly at Points 13, 14, and 12, located in Bukit Raya and Bina Widya Districts, where the number of commercial centers, hotels, and terminals is relatively high, aligning with road lengths exceeding 150 km. However, anomalies also appear, such as

Point 11, which has a road length of 151.05 km but no facilities, potentially indicating an area with specific functions, such as a major transportation route without direct supporting facilities.

4.2.3 Public service and residential area

Additionally, Table 5 presents land use data related to public services and residential areas. In the context of economic activities, the tertiary sector is a category of economic activities that provides services to the community. These services cover various aspects, such as public services by government institutions, healthcare facilities, and educational institutions. These services not only support the well-being of the community but also serve as a key driver for the smooth operation of economic activities, both directly and indirectly.

In addition to land use for public services, Table 5 also provides data on land use for residential areas. Residential areas function as living spaces for the population, who play roles as economic actors, both as part of the workforce and as consumers.

Table 5. Public service and residential area

Point	Healthcare Center (unit)	Government Building (unit)	Educational Building (unit)	Residential (km^2)
1	0	0	0	0
2	0	1	3	0
3	0	1	1	0.13
4	1	8	31	6.65
5	1	0	5	0.50
6	0	1	2	0.20
7	0	0	0	0.06
8	0	2	13	3.84
9	21	34	82	18.36
10	2	3	17	4.21
11	0	0	0	0.03
12	3	2	30	4.86
13	9	10	43	13.83
14	2	4	18	7.21
15	0	3	3	0.86
16	3	6	18	6.72
17	2	2	22	8.35
18	2	2	22	8.35

Based on Table 5, the distribution of facilities and residential areas shows varied patterns across the measurement points. Point 9, located in Payung Sekaki District, stands out as a hub of activity with the highest number of facilities, including 21 healthcare centers, 34 government buildings, and 82 educational buildings, as well as a residential area covering 18.36 km^2. This suggests that the point may represent a city center or a region with highly intensive economic activities. Conversely, in certain areas of Rumbai Barat and Tenayan Raya, points such as points 1, 2, 7, and 11 have very few or no facilities, indicating underdeveloped regions or areas with specific alternative functions.

Overall, there is a tendency for the number of facilities, especially educational and government buildings, to positively correlate with the size of residential areas. This can be observed at points such as points 13 and 14 in Bukit Raya District, where the presence of numerous facilities is accompanied by large residential areas. However, anomalies also exist, such as Point 5, which has several facilities but a relatively small residential area, possibly due to geographic constraints or differing land-use functions in the region.

4.3 Spatial analysis of $PM_{2.5}$ data related to economic activities

This section presents the results and analysis connecting $PM_{2.5}$ data with various economic activities in Pekanbaru City. The analysis begins by outlining the general conditions of $PM_{2.5}$ concentrations based on data collected through sensors across all measurement points. Subsequently, correlation testing is conducted among land use variables, such as plantation area, residential areas, commercial facilities, and other infrastructure, to understand the relationship patterns between these variables. Finally, the analysis focuses on the correlation between land use and $PM_{2.5}$ concentrations, providing valuable insights into the contribution of various economic activities to air quality in Pekanbaru.

4.3.1 Air quality condition in Pekanbaru based on low cost sensor measurements

Based on the sensor measurement results presented in Table 2, the air quality conditions in Pekanbaru can be divided into several categories. According to the Indonesian Air Pollution Index (ISPU) standards for $PM_{2.5}$ concentrations, the $PM_{2.5}$ concentrations are categorized as follows: Good (0 - 15.5 μg/m³), Moderate (15.6 – 55.4 μg/m³), Unhealthy (55.5 – 150.4 μg/m³), Very Unhealthy (150.5 – 250.4 μg/m³), and Hazardous (250.5 – 500 μg/m³). Figure 6 presents a visualization of the $PM_{2.5}$ concentration data for each measurement point based on these categories. This classification provides a clearer picture of the air quality across different areas of Pekanbaru.

Based on the presented $PM_{2.5}$ concentration data, it can be observed that the majority of the measurement points fall within the "Moderate" category according to the Indonesian Air Pollution Index (ISPU) standards, which ranges from 15.6 μg/m³ to 55.4 μg/m³. The point with the highest concentration is point 13, with 53 μg/m³, which is already at the upper limit of the "Moderate" category. Other points, such as point 1 (22 μg/m³), point 2 (15 μg/m³), and point 3 (21 μg/m³), fall at the lower end of this range. $PM_{2.5}$ concentrations within this category indicate air quality that is not optimal, although it can still be considered safe for most daily activities. However, points with higher concentrations, such as point 4 (27 μg/m³), point 5 (33 μg/m³), and point 6 (20 μg/m³), suggest that air quality in certain areas of Pekanbaru has entered the "Moderate" category and may require special attention to prevent long-term health issues, particularly for vulnerable groups such as children, the elderly, and individuals with respiratory conditions. Overall, while no point reached the "Unhealthy" category or worse, there is still a need to improve air pollution control policies to maintain good air quality in Pekanbaru. It is important to note that these conditions represent Pekanbaru during a period without haze disasters caused by forest fires in Riau Province and its surrounding areas.

4.3.2 Correlation of $PM_{2.5}$ with land use related to economic activities in Pekanbaru

In the previous section, data on land use related to economic activities in Pekanbaru was explained, and categorized into three main groups: agricultural activities, industrial and economic infrastructure activities, and public service and residential areas. This section presents the correlation calculations between these land use variables, as well as the relationship between land use and $PM_{2.5}$ concentrations. The primary goal of this calculation is to understand the distribution pattern of economic activities and their relation to air quality in Pekanbaru, as measured by $PM_{2.5}$ concentrations.

Both Pearson and Spearman correlation methods have been applied to analyze the data, and the results show significant differences, particularly in terms of the correlation between industrial data and other variables. The correlation results from both methods are presented as heatmaps, which can be seen in Figures 7 and 8. A review of the land use data from each sampling point, as shown in Tables 3 to 5, reveals that the relationships between the variables are not linear. Therefore, the Spearman correlation method is considered more suitable for further spatial analysis, as this method can better handle non-linear relationships.

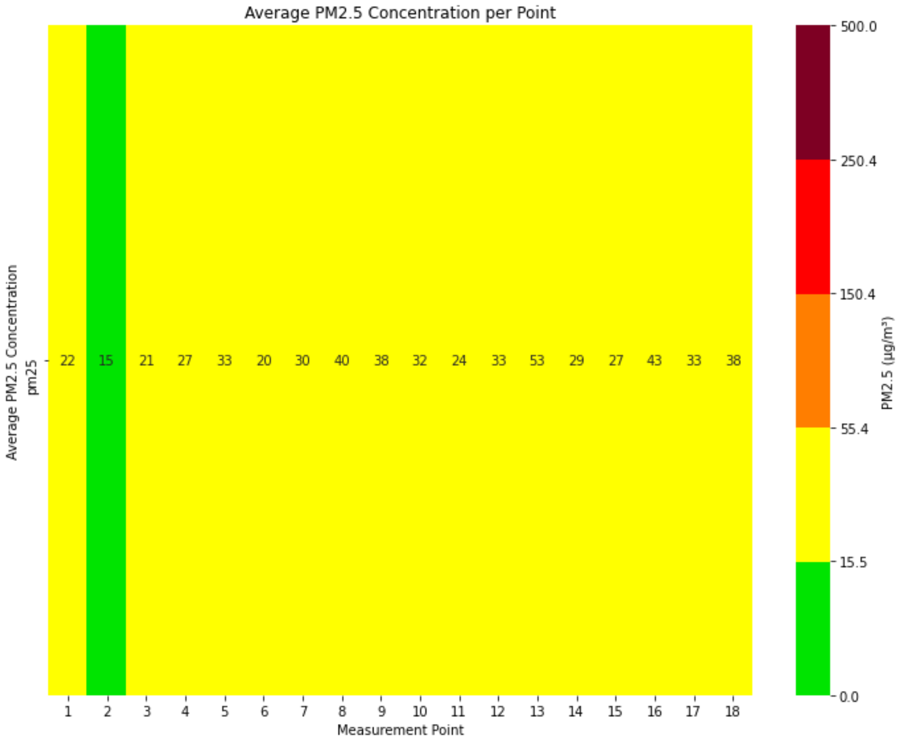

Figure 6. The heat map of $PM_{2.5}$ average concentration at 18 measurement points

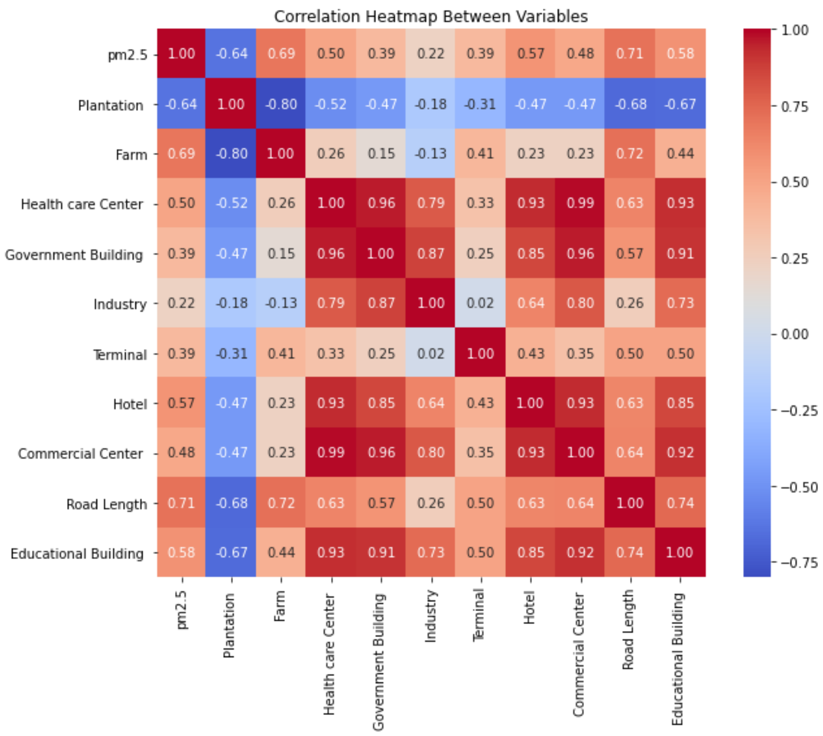

Figure 7. Correlation heatmap between variables using the pearson method

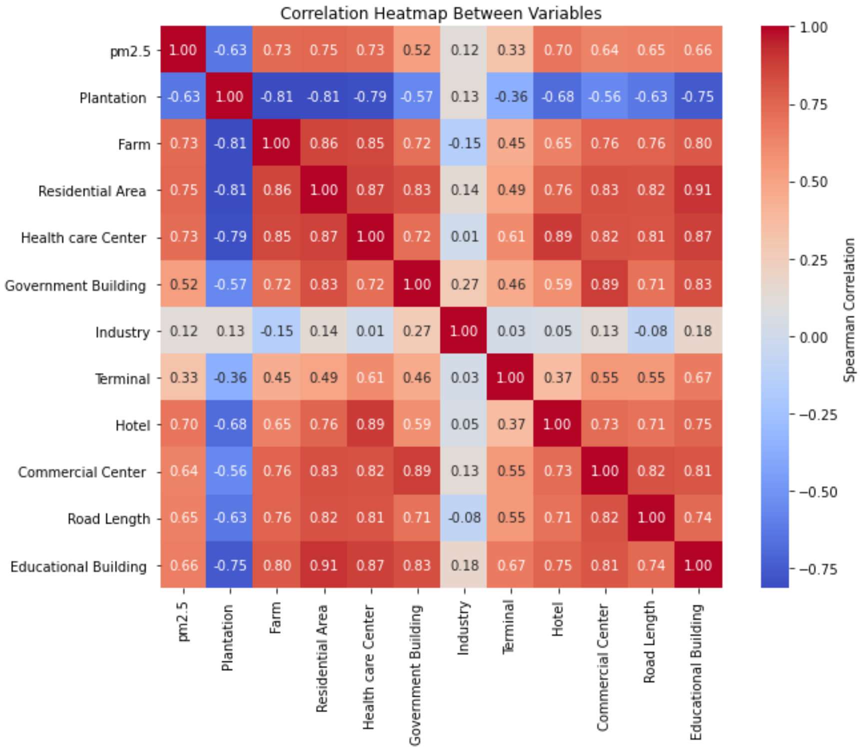

Figure 8. Correlation Heatmap between variables using the spearman method

4.3.3 Spatial analysis of $PM_{2.5}$ concentration based on correlation result

The Spearman correlation analysis reveals a complex relationship between $PM_{2.5}$ concentrations and various environmental and socio-economic variables. A strong positive correlation between $PM_{2.5}$ levels and areas with high economic and social activity—such as residential areas (r=0.75), farmland (r=0.73), healthcare centers (r=0.73), hotels (r=0.7), and commercial centers (r=0.64)—indicates that these locations tend to have elevated $PM_{2.5}$ concentrations. This relationship is further supported by the positive correlation with road length (r=0.65), emphasizing the significant role of transportation in pollution emissions.

Conversely, $PM_{2.5}$ shows a negative correlation with plantation areas (r=−0.63), underscoring the role of green spaces in mitigating air pollution through absorption mechanisms. The weak correlation between $PM_{2.5}$ and industrial areas (r=0.12) suggests that industrial emissions in Pekanbaru are more localized, with minimal impact on overall air quality. Similarly, the correlation with terminals (r=0.33) reflects their limited distribution, which reduces their influence on air pollution.

Areas with extensive residential zones, such as sampling points 4, 9, 10, 12, 13, 14, 16, 17, and 18—located in the districts of Rumbai Timur, Payung Sekaki, Tenayan Raya, Bina Widya, Bukit Raya, Tuah Madani, and Marpoyan Damai—show consistently high $PM_{2.5}$ concentrations. This trend is closely associated with population density, which drives higher economic activity around residential areas. Previous research [23] has explored the impact of population density on air pollution, noting that other factors, such as geography and environmental policies, also play a role. However, in Pekanbaru, the size of residential areas has a clear correlation with $PM_{2.5}$ concentrations.

Farm areas contribute to high $PM_{2.5}$ levels, primarily due to biomass burning, a common practice during agricultural waste disposal or land clearing. Studies have modeled the impact of biomass burning in Southeast Asia [24]. The Pekanbaru region could also experience similar issues. Districts such as Bukit Raya, Marpoyan Damai, Bina Widya, Tuah Madani, and Tenayan Raya are home to significant farmland. On the other hand plantation areas show minimal biomass burning activity. This is reflected in the negative correlation between $PM_{2.5}$ and plantation areas, where larger plantations correspond to lower $PM_{2.5}$ levels. Sampling points in the districts of Rumbai Barat, Rumbai Timur, and Tenayan Raya confirm this trend, likely due to the absence of significant human activity and the beneficial effect of green spaces.

Public facilities, including government buildings, healthcare centers, and educational institutions, show a strong positive correlation with $PM_{2.5}$ concentrations. Districts such as Payung Sekaki and Bukit Raya, which house numerous such facilities, exhibit higher $PM_{2.5}$ levels.

Although industrial areas show minimal correlation with $PM_{2.5}$ due to their concentrated locations (mainly in Tenayan Raya and Bukit Raya), economic activities associated with hotels and commercial centers have a more pronounced effect, as seen in districts like Payung Sekaki and Bukit Raya.

Economic activities, whether related to public services or trade, are linked to higher emissions due to transportation and mobility. Research has demonstrated a strong relationship between traffic density and air pollution, and proposed road network restructuring to mitigate emissions [25]. Another study has suggested congestion reduction models to lower $PM_{2.5}$ emissions [26]. These strategies could also be applied to high-traffic areas in Pekanbaru's economic hubs.

The interaction between variables provides further insights into land-use dynamics. Plantation areas exhibit a significant negative correlation with residential areas (r=−0.81) and healthcare centers (r=−0.79), suggesting land-use competition between green spaces and urban zones. The high positive correlation between residential and healthcare areas (r=0.87), as well as between residential and commercial centers (r=0.83), reflects the spatial interdependence of economic and social functions in urban settings.

Furthermore, commercial centers show a strong correlation with infrastructure variables such as road length (r=0.82) and educational buildings (r=0.81), indicating that accessibility and economic activity play a central role in shaping land-use patterns. The high correlation between educational buildings and residential areas (r=0.91) emphasizes the close proximity of educational facilities to residential zones.

In summary, these variable interactions reveal the complex relationship between land use, human activity, and $PM_{2.5}$ concentrations. Higher $PM_{2.5}$ levels are typically found in areas with dense human activity—particularly in economically and socially active zones—while green spaces consistently correlate with lower $PM_{2.5}$ concentrations. These findings suggest the need for a more balanced approach to spatial planning, with a focus on increasing green spaces and managing economic activities sustainably to mitigate air pollution in Pekanbaru.

Based on the Spearman correlation analysis, the Pekanbaru City government can implement several strategies to reduce $PM_{2.5}$ pollution. These actionable recommendations are designed to address the specific areas identified by the analysis:

- Increase Green Spaces in High-Population Districts.

The government should prioritize the creation and expansion of urban green spaces in districts with high population density and high PM2.5 concentrations, such as Rumbai Timur, Payung Sekaki, Tenayan Raya, Bina Widya, Bukit Raya, Tuah Madani, and Marpoyan Damai. For instance, developing city parks, rooftop gardens, and green corridors along major roads and residential areas can increase green cover and reduce pollution. Establishing green spaces close to healthcare centers and educational facilities can also improve public health by reducing exposure to pollutants. Several studies have also demonstrated that the presence of green spaces can reduce individual exposure to air pollution caused by both human activities and biomass burning [27, 28].

- Regulate Biomass Burning and Promote Sustainable Agricultural Practices.

The government needs to regulate biomass-burning practices on agricultural land in districts that contribute significantly to $PM_{2.5}$, such as Bukit Raya, Marpoyan Damai, and Tenayan Raya. This strategy may include strict monitoring of land clearing through burning and providing incentives for environmentally friendly agricultural waste management methods. Efforts such as those by researchers [29] who developed grid-based emission inventory methods for air quality assessment that could be implemented as a mitigation strategy for open biomass burning.

- Develop a Comprehensive Public Transportation Network.

To reduce transportation-related emissions, the government should invest in improving public transportation systems, especially in Payung Sekaki and Bukit Raya, where road density is high. The introduction of low-emission buses, electric trams, and a dedicated bicycle lane network would decrease reliance on private vehicles and alleviate traffic congestion. Furthermore, incentivizing the use of electric vehicles through tax breaks and establishing charging stations would contribute to cleaner air.

Some studies have also examined how electric vehicles can reduce the impact of air pollution. For example, research [30] shows that the adoption of autonomous electric vehicles could reduce greenhouse gas emissions by up to 34% of total transportation emissions by 2050.

- Incorporate Environmental Sustainability in Urban Planning.

The city should integrate environmental sustainability into its urban planning processes to reduce competition between green spaces and urban areas. This can be achieved by incorporating green building standards and zoning laws that encourage green spaces in residential, healthcare, and educational districts. For example, urban planners could mandate green rooftops for new commercial buildings and ensure that residential areas have accessible parks within walking distance.

- Public Education and Awareness Campaigns.

Increasing public awareness about the importance of green spaces and sustainable transportation is essential. The government could launch educational campaigns on the impact of biomass burning and the benefits of using public transport or electric vehicles. Community engagement programs, such as tree-planting initiatives and carpooling schemes, would encourage citizens to participate actively in air quality improvement efforts.

5. CONCLUSION

The collection of $PM_{2.5}$ data from 18 locations in Pekanbaru over three days revealed a stable concentration pattern, with daily fluctuations influenced by economic activities. Statistical analysis shows that this data is representative of spatial analysis, with a consistent value distribution and most points falling within the "Moderate" air quality category. Although no points reached the "Unhealthy" category, several areas exhibited relatively high $PM_{2.5}$ concentrations, requiring attention.

The air quality, which is mostly categorized as "Moderate," reflects the impact of various economic activities in Pekanbaru, including agriculture, industry, economic infrastructure, as well as public services and residential areas. Residential areas and trade activities in commercial centers and also public services activities are associated with higher $PM_{2.5}$ concentrations, while green spaces such as plantations contribute to the reduction of pollution. Transportation activities, particularly highways and terminals, also show a significant correlation with pollution emissions, reinforcing the role of the transportation sector in air quality.

To reduce $PM_{2.5}$ pollution, the Pekanbaru government needs to implement policies that support the expansion of green spaces in densely populated areas, such as city parks and greening in residential zones. In addition, regulations on biomass burning and the development of an environmentally friendly transportation system, such as electric vehicles, will help reduce pollution emissions. More balanced land-use planning and public education about the importance of reducing air pollution are also crucial steps in improving air quality and public health in Pekanbaru.

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